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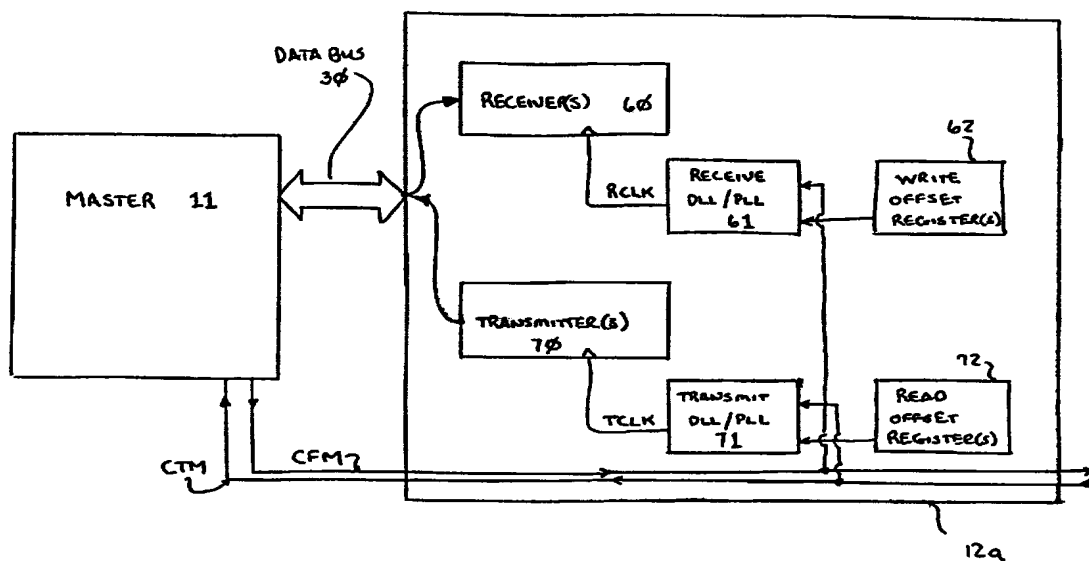
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(54) Title: BUS SYSTEM OPTIMIZATION



(57) Abstract: A bus system comprising a master (11) connected to one or more slave devices (12a-n) via a bus (30) is disclosed. The bus system is able to effectively communicate control information during a calibration phase and to individually determine appropriate timing and/or voltage offsets for each slave device (12). The offsets are used to optimize transfer timing (including duty cycle characteristics), signal equalization, and voltage levels for data exchanged between the master (11) and the slave devices (12a-n).



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BUS SYSTEM OPTIMIZATION

FIELD OF THE INVENTION

The present invention relates to bus systems. More particularly, the present invention relates to a method and apparatus for optimizing the voltage and timing characteristics in a bus system, and to a method for transmitting control information during system calibration.

BACKGROUND OF THE INVENTION

Computer systems and other electrical systems typically use one or more buses to interconnect integrated circuits and other system components. Data, typically in digital form, is communicated between such circuits and components via a bus.

Recent trends in bus development have dramatically reduced the voltage swings associated with different data states on the bus. Early bus systems saw rail-to-rail voltage swings from 3.5 or 5.0 volts down to zero volts. More contemporary bus systems provide voltage swings of less than 1 volt. Limited voltage swings have resulted in reduced power dissipation and lower levels of induced noise on the bus. These reductions are particularly important in the context of bus systems running at ever increasing clock rates.

However, reduced voltage swings and increasing data rates pose considerable problems to the system designer. Reduced voltage swings necessarily provide reduced voltage margins. That is, the ability of system components to distinguish one data state from another on the bus is reduced as the upper and lower swing thresholds move closer together. Similarly, increasing operating frequencies require system components to detect data on the bus during shorter and shorter time intervals. Accordingly, voltage and timing margins for bus signals are often limiting factors in determining overall system performance.

Figure 1 is a simple block diagram of a bus system comprising a master 11 and slaves 12a-12n connected via a data bus 30 and a folded clock signal (Clock-To-Master "CTM" and Clock-From-Master "CFM"). As shown in the related signal timing diagram of Figure 2, valid data is apparent on the data bus during a period T. Ideally, the data signal would be clearly defined at VHI for a first data state and at VLO for a second data state. VHI and VLO would be equally spaced above and below a reference voltage, Vref. Such ideal relationships would provide maximum voltage margin between high and low data states, and

correspondingly optimal signal detection capabilities for system components.

Additionally, data would be detected at time t_1 during the "data eye," i.e., the period ("tbit") during which valid data is on the bus between data transition periods. Time t_1 corresponds to center of the data eye and provides maximum timing margin ($\frac{1}{2}$ tbit) for data detection between data transition periods.

Unfortunately, the ideal voltage and timing margins illustrated in Figure 2 do not exist in actual bus systems. Figures 3A and 3B illustrate typical timing skews between the ideal occurrence of a clock signal within the data eye and actual occurrences. Such clock timing skews arise from many possible sources, such as differences in the manufacture of signal line traces on printed circuit boards, or differences in signal flight time due to the buildup of standing waves induced by signal and clock reflections and noise on signal lines.

In Figure 3A, a CTM signal transition occurs early in the data eye by a period δ before the ideal placement of the CTM transition. In other words, the master reads data from a slave too early relative to the clock by a time δ . In Figure 3B, the CFM signal occurs late in the data eye by the same time. Thus, the master writes data into the slave too late in the data eye by time δ .

Slight differences in the actual timing of the clock signal and/or the data signal will result in a shift of their ideal timing relationship. In addition, the bidirectional nature of some signal lines in the bus system will result in timing shifts of different polarities depending on the direction of data flow.

Each one of the multiple slaves connected to the bus might have a different and unpredictable timing error in relation to the ideal clock placement. Such errors reduce the overall timing margin in the system. Further, as actual transition times wander the hazard arises that a device will attempt to read data during a data transition period, i.e., during a period where the data is not valid on the bus. This hazard increases with system operating frequency.

A comparison between Figures 4A and 4B illustrates the problem of voltages errors in the bus system of Figure 1. In Figure 4A, ideal relationships between VHI, VLO, and Vref are shown, where the voltage swing from VHI to Vref is the same as the voltage swing from Vref to VLO. In one embodiment, VHI is 1.8 volts, Vref is 1.4 volts, and VLO is 1.0 volts. In contrast, the voltage swing from VHI to Vref in Figure 4B is much less than the voltage

swing from V_{ref} to V_{LO} . Such an unequal relationship dramatically reduces the voltage margin for accurately detecting a data value on the bus associated with V_{HI} .

Where the bus system of Figure 1 uses single-ended data and a single reference voltage, as explained below in greater detail, the presence of voltage errors is particularly harmful. For such systems, a reference voltage (V_{ref}) centered between V_{HI} and V_{LO} , such as shown in Figure 4A, would provide maximum voltage margin.

Unfortunately, a number of system phenomenon prevent the stable, centered positioning of V_{HI} and V_{LO} about V_{ref} . For example, channel-DC resistance induces voltages errors in current mode signaling systems. With channel-DC resistance a write data eye can shift in voltage as it goes down the signaling channel. That is, slaves further away from the master are likely to experience smaller voltage swings than the swings of slaves closer to the master, simply due to increasing channel-DC resistance which forms a voltage divider with the termination resistance. In addition, setting output voltage levels to be symmetric about V_{ref} in manufactured systems which experience real process, voltage, and temperature variations is very difficult.

At some point, like the timing errors illustrated above, voltage errors will result in a data error. At a minimum, the presence of voltage errors will reduce the voltage margins allowed within a bus system.

Recognizing the inevitable degradation of the timing and voltage characteristics of bus system signals and the problems associated with same, conventional bus systems sought to compensate for the timing and voltage errors by gross adjustments of the data and/or clock signals in the master. This approach improved signaling margins where degradations were predictable, or where a very limited number of components were connected to a simple bus. However, as bus systems have increased in complexity and size, it has become clear that many factors adversely impacting timing and voltage margins are unique to individual slave devices, or to the relative position of the slave to the master within the overall system.

Thus, the conventional use of timing and voltage offsets in the master has proved ineffective. Similarly, the use of vernier re-calibration techniques has resulted in inconsistent system performance and unacceptable bandwidth degradation in high frequency systems. Accordingly, a need remains for an approach to timing and voltage error compensation which is reliable and well adapted to complex, high frequency bus systems.

SUMMARY OF THE INVENTION

The present invention provides a method and apparatus for effectively adjusting the timing and/or the voltage characteristics of data signals sent via a bus between a master and one or more slave devices. The present invention is particularly well adapted for use in bus systems having a plurality of slave devices since the timing and voltage adjustment may be performed on a slave device by slave device basis. By compensating for voltage and timing skews on an individual basis, the data transfer via the bus may be optimized.

In one general aspect of the present invention, offset values associated with each slave device are used to adjust timing and/or voltage characteristics. Timing and associated offset values may be generally referred to "write" and "read." These terms are used simply to distinguish the direction of data transfer between the master and slave and are not used as limited to classic memory device WRITE and READ operations.

The offset values described in the present invention are typically used in conjunction with a clocking circuit, such as a delay locked loop or phase locked loop, to generate read write clock signals internal to each slave device.

In another aspect of the present invention, a timing adjustment circuit is provided in each slave device to generate an optimized internal read/write clock signal. This internal read/write clock signal is typically derived in relation to a master clock signal applied to the slave device and an offset value.

The timing adjustment circuit may take many forms and may make timing adjustments in absolute time, as well as in degrees. In several of these forms a read/write offset feedback signal is developed in relation to the offset value(s) and used to generate the internal read/write clocking signal.

In a second general aspect, the present invention uses offset values specifically determined with respect to each slave device to adjust the voltage level(s) of data received by the slave device and/or the voltage level or drive current for data being transmitted by the slave device.

The present invention is also directed to an apparatus and method for determining the relevant timing and/or voltage offsets for each slave device in the bus system. The determination of these offsets is often made during a calibration phase of operation for the bus system. During calibration, the bus system may communicate control information using

a protocol or control information packet which differs from the protocol or control information packet used during normal bus system operation.

5 In yet another aspect of the present invention, one or more offset values, either voltage or timing, are stored in one or more registers on the master. A mean or common offset value may be stored in the master and applied to each slave device, or individual offset values corresponding to each slave may be stored in the master and selected, as appropriate, when data is sent to or received from the slave. Thus, the present invention contemplates slave resident adjustment circuits and master resident adjustment circuits for both timing and voltage aspects.

10 In similar vein, duty cycle adjustment may be made within a bus system according to the present invention. Further, signal equalization may also be adjusted using the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a block diagram of a bus system;

Figure 2 is a timing diagram illustrating an ideal relationship between a data eye and a read/write clock signal;

5 Figures 3A and 3B are timing diagrams illustrating typical timing relationships between a data eye and a read/write clock signal;

Figures 4A and 4B are swing voltage diagrams illustrating the difference between an ideal voltage swing and a typical voltage swing;

10 Figure 5 is a block diagram of a bus system showing exemplary channel signaling in some greater detail;

Figure 6 is a block diagram generally illustrating the timing adjustment aspect of the present invention as applied to a typical slave device/master device relationship;

Figure 7 is a circuit diagram showing a first embodiment of a timing offset circuit according to the present invention;

15 Figure 8 is a circuit diagram showing a second embodiment of a timing offset circuit according to the present invention;

Figure 9 is a circuit diagram showing a third embodiment of a timing offset circuit according to the present invention;

20 Figure 10 is a circuit diagram showing a fourth embodiment of a timing offset circuit according to the present invention;

Figure 11 is a circuit diagram showing a fifth embodiment of a timing offset circuit according to the present invention;

Figures 12A and 12B illustrate data transmission timings in an exemplary double-data-rate system;

25 Figure 13 is a block diagram illustrating the addition of a duty cycle offset register(s) to one embodiment of a bus system within the context of the present invention;

Figure 14 is one embodiment of a duty cycle adjustment mechanism adapted for use with the duty cycle registers shown in the system of Figure 13;

30 Figure 15 is a more detailed exemplary circuit showing one possible implementation of the duty cycle adjustment circuit shown in Figure 14;

Figure 16 is a waveform diagram illustrating certain relationships between the signals

apparent in the foregoing duty cycle adjustment circuit;

Figure 17 is another embodiment of a duty cycle adjustment mechanism adapted for use with the duty cycle registers shown in the system of Figure 13;

Figure 18 is a more detailed exemplary circuit showing one possible implementation of the duty cycle integrator shown in Figure 17;

Figure 19 is a more detailed exemplary circuit showing one possible implementation of the duty cycle adjustment circuit shown in Figure 17;

Figure 20 is a block diagram illustrating duty cycle adjustment scheme within the context of the present invention as applied to an N-data-rate system;

Figure 21 is a more detailed exemplary circuit showing one possible implementation of the duty cycle adjustment circuit(s) shown in Figure 20;

Figure 22 is yet another embodiment of a duty cycle adjustment mechanism adapted for use with the duty cycle register(s);

Figure 23 is a block diagram illustrating another duty cycle adjustment scheme within the context of the present invention as applied to an N-data-rate system;

Figure 24 is a block diagram generally illustrating the voltage adjustment aspect of the present invention as applied to a typical slave device/master device relationship;

Figure 25 is a block diagram illustrating a first approach to timing calibration consistent with the present invention;

Figure 26 is a timing diagram illustrating the timing calibration approach shown in Figure 25;

Figure 27 is a block diagram illustrating a second approach to timing calibration consistent with the present invention;

Figure 28 is a timing diagram illustrating a scanning window approach to timing calibration;

Figure 29 is a block diagram illustrating a scanning window approach to voltage calibration;

Figure 30 is a voltage diagram illustrating the scanning window approach of the circuit in Figure 29;

Figure 31 is a block diagram illustrating a first embodiment of a voltage calibration circuit consistent with the present invention;

Figure 32 is a block diagram illustrating a second embodiment of a voltage calibration circuit consistent with the present invention;

Figures 33 is a block diagram illustrating a third embodiment of a voltage calibration circuit consistent with the present invention;

5 Figure 34 is a waveform diagram illustrating an adapted scanning window approach to duty cycle adjustment calibration;

Figure 35 is a waveform diagram illustrating an unequalized data transmission;

Figure 36A and 36 B are exemplary transmitter-side output driver circuits comprising a temporal equalization circuit;

10 Figure 37 is an exemplary receiver-side equalization circuit;

Figure 38 is a block diagram of a bus system highlighting additional channel signals over those shown in Figures 1 and 5;

Figure 39 is a timing diagram illustrating even and odd data packet definitions relative a clock signal;

15 Figure 40 is a block diagram generally illustrating the timing adjustment aspect of the present invention in relation to one exemplary bus system;

Figure 41 is a timing diagram illustrating one exemplary relationship between expanded control packets and normal data packets;

20 Figure 42 illustrates changes in the format of an exemplary control information packet as between normal mode of operation and a calibration mode of operation;

Figure 43 illustrates the changes to a selected exemplary decoding circuit required to implement the different mode of interpretation of the control information packet shown in Figure 26; and,

25 Figure 44 generically illustrates the placement of one or more "offset registers" within the master as compared with the former slave resident registers.

DETAILED DESCRIPTION

In order to better understand the use, implementation, and associated benefits of the present invention, a general bus system readily adapted to the present invention will be described with reference to Figure 5. In the block diagram of Figure 5, a bus system 10, shown in some additional detail with reference to the bus system shown in Figure 1, comprises bus 30 coupled between a master 11 and a plurality of slaves 12a-12n. Bus 30 is a high speed, low voltage swing bus comprising multiple signal lines and transferring data between slaves 12a-12n and master 11.

Master 11 and each slave 12a-12n typically include an interface circuit (not shown) coupling the respective device to bus 30. Within bus system 10, a master can communicate with another master (not shown) and with slaves 12a-12n. In contrast, slaves only communicate with masters.

Master 11 contains intelligence and generates commands to the slaves. Master 11 may be a microprocessor, a digital signal processor, a graphics processor, peripheral controller, an input/output (I/O) controller, a DMA controller, a memory controller, a communications device, or some other type of intelligent controller.

Slaves require only a low level of intelligence. In one preferred embodiment, slaves 12a-12n are DRAMs, but might be one or more other types of memory devices including electrically programmable read only memories (EPROMs), flash EPROMs, random access memories (RAMs), static RAMs (SRAMs), video RAMs (VRAMs), etc. In another embodiment, slaves 12a-12n are bus transceivers.

Master 11 and slaves 12a-12n each includes Data Bus [8:0] pins, at least one BusCtrl pin and BusEnable pin, a ClkToMaster ("CTM") pin, a ClkFrom Master ("CFM"), and a Vref pin. These pins receive and transmit low voltage swing signals and correspond to the channel signal line(s) and buses shown in Figure 5. In the illustrated embodiment, a 9 bit data bus is assumed. However, one of ordinary skill in the art will understand that the data bus might include any reasonable number of signals lines, and is typically part of a larger communication channel having a control bus and/or an address bus.

Master 11 may be configured to communicate control information to slaves 12a-12n in many different ways. The BusCtrl and BusEnable signal paths shown in Figure 1 are typical of such configurations, and may each comprise a single signal line or a number of

signal lines. Further, master 11 and slaves 12a-12n may comprise a daisy chained, initialization signal line connected between the SOut and SIn pins shown in Figure 5.

Data bus signal lines 32 transfer data between master 11 and slaves 12a-12n. The data bus signal lines are transmission lines having controlled impedances. Each data bus signal line 32 is terminated at one end in a termination resistor (collectively shown as 20). The termination resistors are coupled to a termination voltage, V_{term} . The resistance value R of each termination resistor 20 is equal to the line impedance of its data bus signal line 32. Such a configuration helps prevent unwanted signal reflections on the signal line. Other signal lines in memory system 10, such as BusCtrl line 14, BusEnable line 15, CTM line 16a, and CFM line 16b, are similarly terminated, 23, 21, 22, respectively.

Clock line 16 is coupled at one end to a clock 35. In one embodiment, clock 35 is external to and independent of master 11 and slaves 12a-12n. The clock signal generated by clock 35 is carried by clock line 16 to master 11 and slaves 12a-12n. Clock line 16 is folded back to form two line segments 16a and 16b. Segment 16a carries the CTM signal, and segment 16b carries the CFM signal.

Bus system 10 also includes a reference voltage line 17 that couples V_{ref} to each of master 11 and slaves 12a-12n. As shown in Figure 5, voltage V_{ref} is generated in a voltage divider formed by resistors 25 and 26 between termination voltage V_{term} and ground. In addition to V_{ref} , master 11 and slaves 12a-12n are connected to ground (GND) via line 18 and a source voltage V_{DD} via line 19.

In bus system 10, data driven by master 11 propagates past slaves 12a-12n along bus 30. Slaves 12a-12n are able to "sense" the data on the bus in accordance with control information sent from master 11. For example, the master might initiate a transfer of data by broadcasting an access request packet. Each slave 12a-12n decodes the access request packet and determines whether it has been selected to respond. If selected, the slave then responds appropriately by, for example, accepting data from the data bus in a Write operation, or driving data onto the data bus in a Read operation.

The foregoing system is exemplary of systems characterized by single-ended data transmission/reception over a bus consisting of multiple, impedance balanced signal lines. Data is transmitted at a relatively high frequency over these signal lines in relation to a single reference voltage. Such a system is susceptible to the timing errors and voltages described

above.

As will be seen hereafter, the present invention optimizes bus transmission conditions by minimizing overall timing and voltage errors. Operating margins for the system are improved accordingly, and data is communicated with greater reliability.

5 Fundamentally, bus systems operate in two phases; a calibration phase in which system operating parameters may be determined and a normal operation phase in which data is transferred at high speed in accordance with the parameters established during the calibration phase. Effective calibration of the bus system's operating parameters presents a number of concerns which will be discussed in detail below.

10 In a first general aspect, the present invention provides a system and method by which individual slave devices adjust their read and/or write timing to "slave" to a master clock signal. This aspect of the present invention is explained with reference to Figure 6.

Figure 6 further illustrates the relationship between master 11 and slave 12a within the context of the present invention. It is contemplated that all slaves 12a-12n of Figure 5 would be configured as is the slave illustrated in Figure 6, but for the sake of simplicity only one slave is shown. Further, considerable detail unrelated to the present invention has been omitted from the system shown in Figure 6.

Slave 12a comprises one or more receivers 60 and one or more transmitters 70 connected to data bus 30. Data sent from master 11 is communicated via data bus 30 to receivers 60. Data sent to master 11 from slave 12a is placed on data bus 30 by transmitters 70. The construction of receivers 60 and transmitters 70 is conventional and determined by the nature of the slave device and bus system.

Synchronous receipt of data by receivers 60 and synchronous transmission of data by transmitters 70 are respectively controlled by a Receive-clock signal (RCLK) and a Transmit-clock signal (TCLK). These signals are indicative of a class of clock signals gating data to/from the slave device referred to "internal read/write clocking signal." The RCLK signal is derived from the operation of a Receive Delay-Lock-Loop or Phase-Lock-Loop (DLL/PLL) circuit 61 and a Write Offset Register 62. While a DLL or PLL is presently preferred, any clocking circuit capable of accurately generating the internal read/write clock signal in relation to the master clock signal and the offset value may be used. The TCLK signal is derived from the operation of a Transmit DLL/PLL circuit 71 and a Read Offset Register 72.

As seen hereafter, both RCLK and TCLK are preferably derived in relation to the CTM and/or the CFM signals, but any clock signal might serve as the master clock signal.

The Receive DLL/PLL 61 and Transmit DLL/PLL 71 may be separately implemented, or implemented in a single clocking circuit using well understood design principles. For example, commonly assigned U.S. Patent Application 08/795,657 illustrates several possible implementations of a DLL/PLL circuit. U.S. Patent 5,614,855 also discloses a competent DLL circuit.

Write Offset Register 62 stores an offset value established during system calibration or initialization. The stored offset value defines a timing adjustment, as required, to RCLK in relation to the master clock signal (CTM).

For example, the individual timing characteristics of slave 12a in relation to the master clock signal are evaluated and adjusted during the calibration phase of operation, typically during system initialization. If the unadjusted application of the master clock signal to slave 12a results in a Write operation execution outside of the center of the data eye, see Figure 3B, then an offset value corresponding to the timing error δ (lead or lag) is calculated and stored in Write Offset Register 62. This offset value, when applied to the Receive DLL/PLL circuit 61 adjusts the timing of the RCLK signal such that data is accepted from data bus 30 in the center of the data eye, thereby compensating for any Write operation timing errors.

This timing error compensation is made individual to slave 12a, and is maintained, i.e., locked, by the DLL/PLL. The master clock signal remains fixed. No timing adjustment or compensation is required within master 11. The Write timing for each slave in the system may be individually adjusted in this manner.

The same holds true for the Read timing of each slave. The offset value stored in Read Offset Register 72 is similarly defined and applied to adjust, as required, the Read timing of slave 12a.

The block diagram of Figure 6 illustrates the relationship of the timing adjustment circuit(s) to the receivers and transmitters in a slave device, to a master device, and to a master clock signal. Figures 7 through 11 illustrate several embodiments of these circuits in additional detail. Each of these several embodiments is capable of providing an offset in a slave device DLL/PLL without consuming excessive power or occupying a significant area

within the slave device.

The circuit shown in Figure 7 takes full advantage of signals typically apparent in conventional DLL/PLL circuits. In the illustrated example, a 45° block from the DLL/PLL reference loop is acquired along with a 45° earlier version of the output clock taken from the fine loop phase mixer. These inputs are applied to a vector circuit 77 which may comprise two additional 45° blocks and a corresponding load. With this arrangement, vector circuit 77 outputs the original -45° input (C0), a 0° output from the first 45° block (C1), and a $+45^\circ$ output from the second 45° block (C2). The 0° output from the first 45° block is output as either RCLK or TCLK through a matched delay circuit 76.

The three outputs (C0, C1, and C2) from vector circuit 77 are applied to a phase mixer 75. By phase mixing the three signals, phase mixer 75 is able to generate an offset feedback signal varying between -45° and $+45^\circ$. The actual value of this offset feedback signal, which is returned as a feedback control signal to the DLL/PLL, is defined by the offset value stored in the Offset Register (62 or 72). The offset value is applied to Phase Mixer 75 through a digital-to-analog (DAC) converter 74. In this manner, system timing is conveniently adjusted using 45° pull-out sections of the DLL/PLL reference loop. Thus, this embodiment is able to adjust timing of RCLK/TCLK between -45° and $+45^\circ$. Of note, the timing adjustment provided by the circuit in Figure 7 are made in degrees such that the adjustment capability will scale in relation to the system operating frequency.

In contrast, the circuit shown in Figure 8 provides timing adjustment by changing an absolute time delay. The approach implemented by the circuit in Figure 8 can not be scaled with the operating frequency and is more susceptible to manufacturing process, voltage and temperature variations, but it is easy to implement and uses a relatively smaller device area.

In the circuit of Figure 8, the DLL/PLL receives a clock signal or stable frequency source in addition to the CTM and CFM signals which are applied to a transmit phase detector 88 and a receive phase detector 89, respectively. (Alternatively, CTM or CFM may be used as the frequency source). Transmit phase detector 88 also receives the TCLK feedback (Fbk) signal. Receive phase detector 89 similarly receives the RCLK feedback (Fbk) signal. The RCLK and TCLK signals are each output through a respective clock buffer chain 84 and 85.

The feedback signals RCLKFbk and TCLKFbk are adjusted by adding or subtracting

loads and thus adjusting the delay of a chain of invertors, 82 and 83, selected according to the offset value stored respectively in Write Offset Register 62 and Read Offset Register 72. The individual bits of the stored offset values may be configured to drive the enabling nodes and inverter(s) of corresponding MOS capacitors to effect a binary weighted variable load in the feedback paths of RCLKFbk and TCLKFbk to the DLL/PLL circuit.

Another technique for providing timing offset is illustrated by the circuit shown in Figure 9 which is analogous in operation to the circuit shown in Figure 8. This technique uses binary-weighted current sources to place an offset current into the input (front-end) differential pair of the PLL/DLL phase detector. See 88 or 89 in Figure 8. This offset current "pre-tilts" the input comparator one way or the other. This pre-tilt shifts the setup/hold window by adjusting the effective cross-point. The circuit shown in Figure 9 requires a very small area on the slave device, even smaller than the circuit shown in Figure 8. However, it should be recognized that the offset generated in this manner is really a voltage offset which only produces a corresponding timing offset when multiplied by the input edge rate. As a result, the offset is subject to not only process, voltage, and temperature variations, but also variation in the input-edge rate.

With reference to Figure 9, the output of binary-weighted current sources in a first chain of current sources 91 are summed in node A in accordance with a first set (A) of offset bits (1 . . . n). Similarly, the output of binary-weighted current sources in a second chain of current sources 92 are summed in node B in accordance with a second set (B) of offset bits (1 . . . n). The first and second sets of offset bits are stored in an Offset Register, such as the Read Offset Register 72 or the Write Offset Register 62 of Figures 6 and 8.

Another technique for generating a constant (in degrees) phase offset is illustrated in Figure 10. This technique employs a DLL utilizing delay elements with an adjustable supply voltage. In this embodiment, a reference loop control voltage 100 is set by a feedback reference loop 101 to an appropriate value such that the delay of a number of static, or semi-static, gates spans 0 to 180° of the clock period. Reference loop 101 receives an input clock signal and operates with phase detector 102 and charge pump 103. This feedback reference loop output signal essentially sets the supply of the static gates such that their RC time constant is an appropriate fraction of the clock cycle.

The reference loop control voltage (V_C) 100 is used to drive the peripheral loop

interpolators as well as a portion of the main clock (CLK) buffer 105 and feedback clock (FbkCLK) buffer 104. The FbkCLK signal is applied along with the input clock signal to phase detector 110. The output signal of phase detector 110 is applied to Interpolator 111 which also receives selected phase signals from reference loop 101.

5 By virtue of the fact that the delay-vs-supply characteristics of the reference loop buffers and the main and feedback buffers closely track one another, the offset introduced by changing the load capacitance of the feedback clock buffer 104 stays constant over supply and temperature variations. For example, assume that the clock cycle is T_c and the required offset is T_o . The reference loop will set V_c , such that $N \cdot R \cdot C_{ref} = T_c/2$, and offset control
10 register 106 will set the delay of the feedback clock buffer to differ from the main clock buffer by $T_o = M \cdot R \cdot C_{fb}$. Since voltage and temperature variations do not affect N , C_{ref} , M , C_{fb} , and since the reference loop adjusts R such that $N \cdot R \cdot C_{ref}$ always equals $T_c/2$, it follows that the ratio of T_o and T_c stays constant in the first order.

The specific implementation shown in Figure 10 uses digitally controlled capacitance
15 to adjust the delay of feedback clock buffer 104. The same result can be accomplished by changing the resistance of the buffers, i.e., controlling their width, or by multiplexing between two or more of the delay buffers. Both of these alternatives have the property that they generate an offset which stays constant relative to the clock period.

Like the exemplary circuits shown in Figures 7 and 10, the circuit of Figure 11
20 provides timing adjustment in degrees. However, in the embodiment shown in Figure 11, a full offset interpolator 121 is used in conjunction with a primary interpolator 120. Both interpolators receive a set of input or reference vectors from the DLL/PLL reference loop like, for example, those shown in Figure 7. The primary Interpolator 120 generates a feedback signal (CLKFbk) based on the reference vectors and the output of counter 123.
25 Counter 123 receives the output of phase detector 124 which compares the CLKFbk signal with a reference clock signal, such as CTM or CFM.

The output of counter 123 is also applied to adder circuit 125 which adds or subtracts, the offset value (n bits) stored in Offset Register 126. The adder result is then applied to Offset Counter 127, the output of which is applied to Offset Interpolator 121. Based on the
30 references vectors from the DLL/PLL reference loop and the Offset Counter output, Offset Interpolator 121 generates a clock signal (CLK).

Thus, Offset Interpolator 121 uses the same basic input vectors as the primary Interpolator 120 but has an offset register value added or subtracted from its mixing control value. The feedback clock (CLKFbk) used to close the control loop can be either the output of the primary Interpolator 120 (as shown), or that of Offset Interpolator 121, recognizing that difference that one output will have an offset register value opposite (i.e., the polarity is inverted) that of the other.

The implementation illustrated in Figure 11 provides an arbitrary phase offset, i.e., one ranging a full 360°. Since this offset is provided in degrees rather than absolute time (picoseconds of adjustment) the offset is stable with respect to PVT and frequency. Its size is comparable to that of the foregoing exemplary implementations.

Up to this point timing errors have been described in the context of read/write clock signals skewed in relation to data eyes. Using any one of the mechanisms described above, a properly adjusted read/write clock signal may be developed for each slave device to maximize clock signal margins in relation to data appearing on the data bus. For the sake of clarity, the examples illustrated above described data being communicated on one edge of the read/write clock. However, many contemporary bus systems communicate data between a master and one or more slaves using more than one edge of a clock signal or using multiple clocks having different phases. Alternatively, contemporary systems communicate multiple bits in relation to a single clock edge, but using different phase offsets. The use of multiple clock edges or multiple clocks at different phases results in an additional source of timing errors in the bus system, namely duty cycle errors. This problem is illustrated for an exemplary double data rate (DDR) system in Figure 12A and 12B.

In a DDR system, two bits of data are transmitted on one or more data bus lines during each clock cycle. These two bits are often referred to as "even" and "odd" data bits. Double data rate transmission may be accomplished in many ways, but two are illustrated here. In Figure 12A, a single internal clock (tclk) is used to set the duration of data transmission on the bus for both the even and odd data bits. In the example, even data is referenced to the high state of internal clock tclk and the odd data is referenced to the low state of tclk. The duty cycle of tclk is defined to be $T_{\text{high}}/T_{\text{cycle}}$. Further, since the "width" of the even data bit transmission cycle (or data eye) is defined by the duration of the high state of tclk, a second duty cycle, or a "data duty cycle" may be defined. The data duty cycle is the

width of the even data eye divided by the sum of the widths of the even and odd data eyes, i.e., $T_{\text{even}}/(T_{\text{even}}+T_{\text{odd}})$. It should be noted that $T_{\text{even}}+T_{\text{odd}}$ will typically be less than T_{cycle} due to signal jitter. The data duty cycle will be approximately equal to the clock duty cycle, although there may be slight differences if there are other odd/even offsets in the system. A similar DDR system might be constructed using a single clock, where the widths of the data eyes (odd and even) are set by the cross points of the true and complement forms of the clock rather than by the rising and falling edges of the clock

Figure 12B shows an analogous system that uses two clock signals, tclk_E and tclk_O . The falling (or rising) edge of tclk_O defines the beginning of the odd data eye and the falling (or rising) edge of tclk_E defines the beginning of the even data eye. For this system, the duty cycle of interest is actually defined by the difference between these two falling edges divided by the cycle time, rather than by the duty cycle of either clock signal. The data duty cycle may be defined as above.

The timing diagrams of Figures 12A and 12B are drawn with reference to data transmission clock (tclk). Similar diagrams might be drawn with reference to a data reception clock (rclk). However, when drawn with reference to the data reception clock, the right half of the even data eye and the left half of the odd data eye are encompassed by the high state of the rclk . As with the transmission clock example illustrated above, a differential reception clock with timing set at the crosspoints, or two single ended clocks with falling (rising) edges might be used to establish the requisite data reception eyes.

The present invention may be used to properly adjust duty cycle(s) in relation to a transmission and/or a reception clock. Further, the present invention has application beyond DDR systems. For example, the present invention might be adapted for use in a Quad Data Rate (QDR) system in which timing for data exchange is set by four clocks spaced 90° apart. In QDR systems there are actually four different data duty cycles, each data duty cycle being defined as the width of an eye for a given data bit divided by the width of all data eyes. One of ordinary skill in the art will see that the following principles may be applied to any N-Data Rate system, where N is a whole number.

No matter the actual number of clock signals or edges, the overall timing margin of the bus system is limited by the width of the smallest data eye defined by a duty cycle. Thus, for maximum timing margins, the data duty cycle should be as close to $1/N$ as possible, where

N is the number of duty cycle defining clock signals or edges in the system.

However, the variable effects described above combine to skew duty cycle data eyes. Offsets in the system clock or in the internal clock generation circuits will result in duty cycle timing errors which reduce timing margins and compress overall system timing requirements. Thus, adjustment of the clock signals defining erroneous duty cycles is required to optimize system bus performance.

Read duty cycle adjustment and/or write duty cycle adjustment may be accomplished in a manner similar to that discussed above in relation to read/write clocks. For example, as shown in Figure 13, a write duty cycle offset register 63 and/or a read duty cycle offset register 73 may be added to the structure shown and described in relation to Figure 6. The Receive DLL/PLL buffer 61 and the Transmit DLL/PLL buffer 71 are modified to accept and use the read/write duty cycle offset values stored in registers 63 and 73. These read/write duty cycle offset values are used to adjust the duty cycles of the clock signals produced by these buffers.

Duty cycle adjustment does not necessarily require active clock recovery, as provided by the DLL/PLL. Duty cycle adjustment might equally apply to a system where skews between internal and external timing points are compensated outside the slave devices, outside the master, or outside both the master and slave devices.

In other words, duty cycle adjustment may be accomplished not only by use of offset registers located on individual slave devices, but also by use of one or more global offset register(s) resident in the master. A single "mean" duty cycle offset value might be stored in the global register and communicated to individual slave devices, or a plurality of individualized duty cycle offset values might be stored and communicated on an individual basis to respective slave devices or group of slave devices. The one or more duty cycle offset register(s) might alternatively be stored outside the master or slave devices.

One embodiment of a duty cycle adjustment circuit is shown in Figure 14. This circuit, preferably residing within the DLL/PLL buffer circuit, comprises a current mode output digital-to-analog converter (DAC) 140 receiving the duty cycle adjustment values from read/write duty cycle offset register (63/73). In response to the duty cycle adjustment value received, DAC 140 produces two current signals I_{OFFSET} and I_{OFFSET} which are applied to duty cycle adjustment circuit 141

In a nominal case, wherein no duty cycle adjustment is required, I_{OFFSET} and I_{OFFSET} are equal and the differential input signal clkin passes through duty cycle adjustment circuit 141 unchanged to form output signal clkout . The clkout signal is then converted by a differential to CMOS converter circuit 142 to form a single ended clock for uses in the receiver or transmitter circuits. Alternatively, differential to CMOS converter circuit 142 may be replaced by a differential buffer/amplifier which would produce a differential clock signal of appropriate strength to drive the receiver or transmitter circuits.

If there is some difference in the current signals I_{OFFSET} and I_{OFFSET} , the differential waveforms clkout and clkout will be shifted in relation to one another. This shift in relationship will change their differential duty cycle. As presently preferred, the ratio $(I_{\text{OFFSET}}, I_{\text{OFFSET}}) / I_{\text{OUT}}$ will be relatively constant resulting in better independence from voltage and temperature drifts. The duty cycle change will be reflected in the output clock signal (CLK) produced by differential to CMOS converter 142.

The above circuit performs duty cycle adjustment in an "open-loop" manner. That is, no feedback mechanism exists between the corrected clock signal and the duty cycle adjustment circuit. Accordingly, the system must either have sufficient timing margin to work following a single calibration cycle during initialization, or the system must perform periodic re-calibrations.

A presently preferred embodiment of the duty cycle adjustment circuit 141 of Figure 14 is shown in Figure 15. The circuit shown in Figure 15 receives I_{OFFSET} , I_{OFFSET} , I_{OUT} , clkin and clkin as inputs, and generates clkout and clkout as outputs. Relationships between these signals are further illustrated in Figure 16.

Another exemplary embodiment of the duty cycle adjustment circuit is shown in Figure 17. The circuit like the one described in Figure 15 comprises a DAC 170 receiving the duty cycle offset values from duty cycle offset register 63/73 and duty cycle adjustment circuit 172 receiving clkin and clkin and outputting clkout and clkout to differential to CMOS converter 173 which produces the output signal (CLK).

However, this embodiment further comprises a feedback path formed by duty cycle integrator 171 and CMOS to differential converter 174. One embodiment of duty cycle integrator 171 is shown in Figure 18.

In addition to I_{OFFSET} and I_{OFFSET} , duty cycle integrator 171 receives a differential

feedback clock signals FBin and FBin. The differential feedback clock signals FBin and FBin steer the bias current (I_o) 180 using differential pair 181a/b. If the feedback clock has a 50% duty cycle, these two current signals will be equal and the voltage difference at nodes co and co will not change. If, however, the duty cycle is not 50%, then a voltage difference will rise or fall as the current is integrated into capacitors 182a/b.

The output of this duty cycle integrator shown in Figure 18 is applied to the duty cycle adjustment circuit of Figure 19 where it steers current in the differential pair 190a/b. As with the duty cycle adjustment circuit described in Figure 15, the difference in currents I_a and I_b will shift the clkout and clkout currents one to another, thereby changing the duty cycle.

In principle, this duty cycle adjustment scheme should produce the desired clock signal duty cycle without the effect of the duty cycle adjustment value applied from the duty cycle offset register. In practice, however, device mismatches in the duty cycle integrator (171 in Figure 17 and Figure 18) and in the CMOS to differential converter (174 in Figure 17) will not be compensated out, so the optimum adjustment value for the duty cycle offset register will sometimes be nonzero. Current mirrors 185a/b of Figure 18 add the differential offset current I_{OFFSET} to the integration nodes co and co. This will cause the system to reach equilibrium for a FBin duty cycle of other than 50%. Thus, by changing I_{OFFSET} based on the duty cycle adjustment value stored in the duty cycle offset register (63/73), the duty cycle of the clock (CLK) can be properly adjusted. Any value for I_{OFFSET} and I_{OFFSET} will require a compensating duty cycle adjustment on FBin and FBin to be made by the feedback loop formed by duty cycle adjustment circuit 172, differential to CMOS converter 173, CMOS to differential converter 174, and duty cycle integrator 171. As with the embodiment shown in Figure 15, the ratio of $(I_{\text{OFFSET}}, I_{\text{OFFSET}})/I_o$ is relatively constant.

The precepts and relations taught by the exemplary circuits above, may be generically extended and applied to systems having N clocks producing N-Data Rate signals. Conceptually this application is illustrated in Figure 20 in which a plurality of duty cycle offset values 201 (a . . . n) are respectively applied to duty cycle adjustment circuits 202 (a . . . n) to properly adjust input clock signals clkin (a . . . n). In this embodiment, each clock signal is delayed by a corresponding duty cycle offset, but a single mean duty cycle offset value might be applied to each duty cycle adjustment circuit.

In one preferred implementation, each duty cycle adjustment circuit 202 in Figure 20

comprises the circuit shown in Figure 21. This circuit's behavior is analogous to that of the circuit shown in Figure 8. In the circuit of Figure 21, clock signal delay is adjusted by adding or subtracting loads from a chain of inverters 210, which are selected according to the duty cycle offset value stored in duty cycle offset value register 211. By adjusting the relative delays of the N delay adjustment circuits 202, the size of the N-data eyes can be individually defined.

A variation on this scheme would be to use N-1 buffers rather than N, wherein the size of the Nth data eye corresponding to the Nth clock is defined by moving all the other clock eyes relative to the this last clock. In another related embodiment, the constant delay buffers of Figure 10 would be used instead of the inverters of Figure 8. This scheme would have the advantage that delay adjustments would not change with environmental conditions.

In yet another embodiment drawn in relation to a DDR system, the circuit shown in Figure 22 is used to provide appropriate delay adjustments. The circuit of Figure 22 is identical to that of Figure 17 except that the DAC and the duty cycle offset port in the duty cycle integrator have been replaced. The offset is provided by skewing the differential feedback clock FBin1 using delay adjustment circuits 220a/b receiving duty cycle adjustment values from registers 221a/b before feeding it as FBin2 into the duty cycle integrator 171. The delay adjustment circuits 220a/b may be similar to the circuits shown in Figures 8 or 10.

The embodiment shown in Figures 20 and 21 is designed to effect duty cycle adjustment in a slave device. However, it is also possible to adjust the duty cycle on the master using similar schemes and circuits. Of course, master resident circuits to accomplish duty cycle adjustment will consist of a single duty cycle adjustment register storing a single "mean" duty cycle adjustment value, or a plurality of registers storing duty cycle adjustment values for each respective slave device. In the later implementation, the master selects the appropriate duty cycle adjustment value on the basis of the slave device having data written to it or having data read from it.

Figure 23 illustrates another embodiment of a duty cycle adjustment circuit correcting multiple clocks. In this scheme, the individual clocks are produced from differently phased clock signals ($\phi 1$, $\phi 2$, $\phi 3$) coming from Voltage Controlled Oscillator (VCO) or delay line 230. (Any reasonable number of phased clock signals may be used, but three are shown in this example). Based on the duty cycle adjustment values stored in duty cycle registers 233

(a . . . n), phase selectors/interpolators 232 (a . . . n) adjust the exact timing of the output clock edges in relation to a nominal value. Movement of these clock signal edges change the sizes of the corresponding data eyes. In another variation of this scheme, phase selector/interpolator operation is controlled both by the duty cycle adjustment value and the overall phase adjustment register used to set the phases of all the internal clocks to desired relationships with respect to a reference clock.

In addition to timing errors, voltage errors frequently plague bus systems. Voltage errors and their effects were illustrated in the discussion of Figures 4A and 4B above.

In a second general aspect, the present invention provides a system and method by which individual slave devices adjust or compensate the voltage of data received from the data bus, and/or adjust the voltage/current of data being driven onto the data bus. Analogous to the timing adjustment techniques described above, voltage adjustment takes place on a slave by slave basis.

During voltage adjustment, the output voltage swing is properly set and any voltage offset in the received data is compensated. These two functions may be accomplished in many specific ways. Fundamentally, after the master output swing and input levels are optimally established, the resulting signal levels are considered reference, and both slave input offsets and slave output voltage/current are adjusted to correspond to these references.

Figure 24 illustrates a basic approach to voltage adjustment in which signals received from data bus 30 at the front end of a receiver 60 (only a portion of which is shown) are input to a differential compensating amplifier 240. The write data voltage levels are compared to V_{ref} and adjusted in accordance with a write voltage offset value stored in voltage offset circuit 241. Similarly, the output current of driver 242 is adjusted in accordance with read voltage offset value stored in a current control circuit 243. This example assumes a slave output scheme based on controlled current source output drivers, but is readily adapted to other forms of output drivers.

In the approach illustrated in Figure 24, the master contains the more extensive logic and control circuitry required to calibrate the output current level and input voltage offset for each slave in the system. As there are typically many more slaves than masters in a system, the overall system impact of the voltage calibration and adjustment components is minimized. Further, slave die space is conserved.

The exemplary circuits shown in Figures 7 through 11 illustrate several embodiments in which one or more offset values are used to adjust read/write timing to the center of a prescribed data eye. By adjusting read/write timing on a slave by slave basis, the effects at each slave can be compensated for individually and independently. Further, the exemplary circuits shown in Figures 13 through 23 illustrate several embodiment in which one or more offset values are used to adjust read/write clock duty cycles. In order to adjust read/write timing (including duty cycle) on a slave by slave basis, the one or more offset values must be determined and stored for each slave device.

The process of determining and storing the slave offset value(s) is performed during the calibration phase of system operation. The calibration phase typically occurs during system initialization, but may be performed otherwise, For example, calibration may be performed periodically or upon detection of some threshold number of bit errors. The actual determination of the timing offset values may be done using many different techniques. Several techniques are described below.

One technique is referred to as 90° calibration, and it requires the use of a DLL/PLL on the master capable of shifting its clock output by 90°. Together, the block diagram of Figure 25 and the timing diagram of Figure 26 illustrate this technique which is used to calibrate the master-transmit-to-slave, or the write path.

In Figure 25, master 11 comprises a transmit DLL/PLL having a normal (0°) output clock signal and a calibration shifted (90°) internal transmit clock signal. During the calibration phase, master 11 selects the calibration shifted output clock, and then transmits a data sequence to receiver(s) 60 in slave 12a. (Some considerations for a proper calibration phase data sequence are discussed below). Given a data eye corresponding to the normal output clock from the transmit DLL/PLL of master 11, a properly centered slave receive clock would transition in the center of the data eye. See signal A in Figure 26. However, since the calibration shifted internal transmit clock signal offsets data by 90°, a centered transition of the slave receiver clock "A" will now occur at the center of the data transition region instead of the center of the data eye. In cases where the slave receiver clock is too early, signal A' in Figure 26, or too late, signal A" in Figure 26, the transition will not occur at the center of the data transition. Assuming that the data pattern used during calibration has a balanced number of 0 to 1 and 1 to 0 transitions, then this result allows slave receiver 60 to

operate as a phase detector.

For example, assuming a data transition from a "0" to "1" on the data bus line into the slave receiver, the early occurring slave receiver clock transition A' would consistently produce a "0" output. Similarly, the late occurring slave receiver clock transition A" would consistently produce a "1" output. Thus, the data output by the slave receiver can be used to determine phase information during the calibration phase. The slave receiver data derived from this calibration process can be stored in the slave and returned to the master during a subsequent read operation.

The foregoing capabilities can be used by system designers to define an appropriate write offset value. Many different algorithms may be implemented as a matter of routine design choice which result in a "centering" write offset value in a minimum of time and resources. For example, a simple single data transition might be written from master 11 to slave 12a in a large block of data, say 128 bits consisting of 64 ones followed by 64 zeros. These bits are stored in the slave and read back to the master. The master determines where in the data block a one-to-zero transition occurred, and uses this information to increment or decrement the read offset value. This sequence of steps continues until the offset value dithers back and forth between "0" and "1" (i.e., "toggles") with each iteration at which point a centering offset value has been obtained.

Conceptually, the foregoing technique extends conventional DLL/PLL locking loop techniques to implement timing offset control by building a distributed pseudo-DLL using the slave receivers as phase detectors. Thus, assuming the presence within the master of a 90°-shiftable DLL clock, the additional hardware required to implement timing calibration is minimal. Once the output of the data receiver(s) toggle, the distributed loop can be "locked," and the timing of the master output clock returned to normal (0°).

A similar approach to slave transmitter clock calibration (i.e., read offset value determination) can be readily discerned from the foregoing. In this approach, the internal receive clock is shifted by 90° and the master data receivers function as phase detectors. The process of transmitting a block of data, looking for tell-tale data transitions, adjusting the offset value, and repeating until determination of the optimal read offset value, is performed as explained above, except the consideration that data flow is reversed between the two processes. Figure 27 illustrates this approach and the presence of a Receiver DLL/PLL 145

having an output clock which is shiftable by 90° .

The circuits shown in Figures 25 and 27 require that the transmit and receive DLL/PLL on the master incorporate circuits providing the 0° and 90° shifted clock signals. However, such area consuming circuits are not required in the more numerous slave devices, and such phase-shifted clocks are easily available in many DLL/PLL designs. Thus, these configurations accomplish the purposes of the present invention with reduced overall system costs.

Another approach to timing calibration uses a "scanning window," as illustrated in Figure 28, to determine an appropriate offset value for slave read or write timing. During calibration the offset interpolators are scanned across a data window as the master searches for a transition from a passing region to a failing region, i.e., a data transition from 0-to-1, or 1-to-0. One way to accomplish this scanning effect is to provide a register in the master (or slave) DLL/PLL having a range of offset values. By scrolling through the range of offset values and applying each value to the read/write clock, the clock transition will move in relation to the data eye. One offset value will find the leading edge of the data eye and another offset value will find the lagging edge of the data eye. After the master has located both edges of the passing window of the data eye and identified the two corresponding offset values, the master can then take the two offset values and interpolate half-way between them to find the center position for the read/write clock relative to the data eye.

Once an appropriate offset value has been determined, it is written to the corresponding offset register in the slave. Alternatively, the offset scanning may be done by offset interpolators in the slave device. However, the first approach of locating the required interpolators in the master saves overall area in the system.

As illustrated in Figure 24, one or more offset values are used to adjust slave read/write voltages in relation to V_{ref} . By adjusting the read/write voltages on a slave by slave basis, V_{ref} is maintained as a reference and voltage effects are compensated at a local level rather than forcing a system level compensation scheme. In order to adjust the read/write voltages on a slave by slave basis, the one or more offset values must be determined and stored in the voltage offset circuit and current control circuit of Figure 24, or equivalent circuits.

The process of determining and storing the voltage offset value(s) is performed during

the calibration phase like the process for determining and storing timing offset value(s). The actual determination of the voltage offset values may be done using many different techniques. Several techniques are described below.

5 The first technique for calibrating slave voltages, i.e., determining the voltage offset values, is illustrated in Figures 29 and 30. Analogous to the timing calibration scanning window approach, this technique uses a scanning window to calibrate slave voltages. That is, the scanning window feedback mechanism is applied to voltages instead of timing.

10 The circuit shown in Figure 29 assumes a voltage calibration directed to the input (or write) voltage swing for data transmitted from the master to the slave. As data is written from master 11 to a receiver in slave 12a during calibration, its voltage level is compared in 290 with an externally supplied Vref signal. The comparison result is feedback through control logic 291, Vref register 292, and a DAC 293, to an offset-port of a stabilizing (1X) amplifier 294. The nature of node "a" in Figure 29 is determined by the nature of the Vref signal. Where Vref is an externally generated, or otherwise voltage controlled signal node "a" will
15 comprise an adder circuit or other means for combining the two signal paths. Alternatively, where Vref is generated internal to the slave device by the value stored in an offset register, the adder circuit may be omitted.

20 As with the scanning window approach described above, high and low pass/fail transition points are identified. Vref on the slave is set in accordance with a final adjustment offset value located half way between the offset values corresponding to the high and low pass/fail transition points.

25 In another technique write voltage calibration is accomplished through the use of voltage offset cancellation loops located in the slave receiver(s). This technique is illustrated in Figure 31 in which master 11 actually drives the slave's Vref. Master 11 comprises a switch 310 between a nominal Vref generator 311 and a Vol voltage source 312. During write voltage calibration master 11 switches the slave Vref to Vol, and simultaneously drives Vol on its output drivers 315.

30 Slave 12a is placed in write offset calibration mode wherein each slave receiver compares the received data signal at Vol with the "master" Vol signal applied through the Vref signal line. This comparison takes place in voltage cancellation loop 318 which consists of a slave receiver acting as a comparator 317 and offset cancellation circuit 319. Voltage

offset values are applied (added and subtracted) through offset cancellation circuit 319 of the slave receiver until its output toggles at which point the offset loop is locked. Offsets due to manufacturing defects in the slave receiver and/or I*R drops present in the data bus are eliminated in this fashion.

5 In another adaptation of the circuitry shown in Figure 31, a binary master current control value is simply right-shifted by one bit to half its value. The resulting value is applied to output driver 315. The slave accordingly compares the output of driver 315, V_{ol} at half its normal current, to V_{ref} . An offset cancellation loop is run as above until the output toggles.

10 Read voltage output swings for the slave are similarly calibrated. For example, in Figure 32 a current control register 320 in slave 12a is right-shifted by one bit in order to drive half the nominal output value from a slave transmitter. A corresponding receiver in the master samples the output level of the returned data signal and compares it to V_{ref} . An up/down signal resulting from this comparison is feedback to slave 12a via a feedback signal line. The up/down signal is applied to increment or decrement a slave current control value in
15 a current control register 321 until the output of the master receiver toggles at which point the output swing loop is locked. This loop also compensates for DC channel resistance since the "sense" element in the path, i.e., the master receiver, is the same element used to detect read data transmissions.

20 Alternatively, the read output voltage swing may be calibrated using a circuit like the one shown in Figure 33. Here, slave 12a transmits both a "1" and a "0" on different data bus lines 335a and 335b. Master 11 comprises a precision resistive divider 330 which receives these signals and combines them to form an output voltage of $V_{swing}/2$. This output voltage is then compared to V_{ref} in a master data receiver. The result of this comparison is then sent back to slave 12a as an up/down signal and applied to a current control register 331 which is
25 incremented or decremented accordingly until the output of the "comparator" data receiver in the master toggles between 0 and 1.

30 As with timing and voltage calibration, there must be a way of determining the appropriate values to program into the duty cycle adjustment registers. This can be readily accomplished using a modified version of the scanning window illustrated in Figure 28. The modified scanning window is illustrated in Figure 34. Instead of a single set of curves corresponding to varying values of the offset register, there are multiple sets, each

corresponding to a different value for the duty cycle adjustment offset. Each set has the same duty cycle, but differing phases, depending on the duty cycle adjustment offset value. As before, the duty cycle adjustment offset values are scrolled through to find the leading and lagging edges of the data eye. However, for duty cycle calibration, this procedure must be
5 run N times for an N-data rate system in order to find the edges of each eye.

The example shown in Figure 34 illustrates this procedure for a DDR system, where the scrolling is performed twice, once to find the edges of the even eye and once to find the edges of the odd eye. The procedure is repeated for each value of the duty cycle offset register. The device chooses the duty cycle offset values which make the width of the even
10 and odd eyes most closely equal.

If the relationships (i.e. the mapping) between duty cycle adjustment offset values and the corresponding eye sizes are known, a second method can be employed. Namely, the size of each eye is measured using nominal duty cycle offset values, then the appropriate register values are chosen to make the eyes of equal size based on the known the relationships.

If the relationships are not known, they can be estimated by setting the duty cycle
15 adjustment offset values to the extremes of their ranges and then scrolling and measuring the sizes of the eyes. Appropriate values can be chosen by interpolation between the measured duty cycles at the extremes.

Another approach would be simply to measure the overall size of the composite eye,
20 and choose the duty cycle offset register settings that made this size the largest.

Until now, timing (including duty cycle) and voltage adjustments have been discussed as separate phenomenon. While various adjustment mechanisms have been described which address these problems separately one of ordinary skill in the art will recognize that timing adjustments and voltage adjustments are better viewed as a related family of operating system
25 parameters. Effective bus optimization seeks to maximize both timing and voltage margins, although improvements to one or the other will remedy different system performance problems. Recognizing the interplay between signal timing and signal voltage requirement, the concept of signal equalization will now be addressed.

Signal equalization parameters can also be adjusted to increase voltage margins for
30 data signals on the system bus. Equalization involves dynamically changing the drive strength of a channel output driver to compensate for noise signals on the bus. Noise signals

may arise from many sources including adjacent channel crosstalk, or residual or undesired signal reflections on the bus. No matter their nature or origin, noise signals cause signal voltages to vary from one clock cycle to another. Compensation for signal voltage variations due to residual signals on the channel is referred to as "temporal equalization."

5 Compensation for signal voltage variations due to inductive coupling from neighboring channels is referred to as "cross-talk (or spatial) equalization."

Temporal and cross-talk equalization are discussed separately below. It should be noted that the circuitry to accomplish both forms of equalization may be resident in a master transmitter or in respective slave transmitters.

10 Figure 35 illustrates a signal waveform on a hypothetical channel that results from an unequalized transmission of data having a logic pattern 0, 1, 1, 0. The voltage on the channel rises to VOH during transmission of the first logical 0 and then drops toward VOL during transmission of the first logical 1. As shown, the voltage on the channel does not reach VOL during transmission of the first logical 1 and instead reaches a local minimum 200mV above
15 VOL. By contrast, the voltage on the channel drops 100 mV below VOL during transmission of the second logical 1. Finally, the voltage on the channel reaches a local maximum 200mV below VOH during transmission of the final second logical 0.

The foregoing illustrates how signal voltage on a channel is affected by prior transmissions on the same channel. In general, a logical 1 that follows transmission of a
20 logical 0 is less likely to reach VOL than a logical 1 that follows transmission of another logical 1. Similarly, a logical 0 that follows a logical 1 is less likely to reach VOH than a logical 0 that follows another logical 0. Both these effects result in reduced voltage margin at the receiver, making the system more susceptible to errors caused by noise and other margin-reducing effects.

25 Figure 36A illustrates an output driver 700 that includes temporal equalization circuitry according to one embodiment of the present invention. A data signal, Dataj, is used to gate a weighted driver 701. When Dataj is a logical 1, the weighted driver 701 is turned ON to a degree determined by a current control value (CCTL) in register 703 so that a current I_{SIG} flows through driver 701. Weighted equalization drivers 702A-702K are similarly gated
30 by respective prior versions of the data signal (Dataj-1, Dataj-2, ..., Dataj-K) to sink equalization currents I_{EQ1} through I_{EQK} . Thus, the total current that flows through R_{TERM} is

given by: $I_{OL} = I_{SIG} + I_{EQ1} + I_{EQ2} + I_{EQK}$, with each of the I_{EQ} terms being controlled by equalization coefficients stored in respective equalization registers 704A-704K. Because the output voltage V_{OUT} is equal to

$V_{TERM} - I_{OL} * R_{TERM}$, V_{OUT} can be equalized to compensate for prior outputs by appropriate setting of equalization coefficients.

Figure 36B illustrates an embodiment of output driver 700 in greater detail. As shown, the weighted driver 701 includes N binary weighted transistors (1x, 2x, ... 2N-1x) so that I_{SIG} is given by $Data_j * CCTL * I_{UNIT}$, I_{UNIT} being the current through the 1x transistor when active.

Data history generator 705 receives $Data_j$ and a transmit clock signal, $tclk$, and generates K delayed data signals, $Data_{j-1}$ through $Data_{j-K}$. In one embodiment, a new data value is transmitted at each rising edge and each falling edge of $tclk$. Thus, the delayed data signals are generated by passing $Data_j$ through a sequence of flip-flops 706A-706K that are alternately clocked by falling and rising edges of $tclk$. By this arrangement, flip-flop 706A outputs $Data_{j-1}$, flip-flop 706B outputs $Data_{j-2}$ and so forth to flip-flop 706K which outputs $Data_{j-K}$. In an alternative embodiment in which data is transmitted on only one clock edge per cycle of $tclk$ (i.e., one data value per clock edge instead of two), flip-flops 706A-706K may be clocked by same edge of $tclk$.

Equalization driver 702A includes a multiplexer 709, a set of additive logic gates 712A-712R and corresponding binary weighted transistors (1x, 2x,..., 2R-1x), and a set of subtractive logic gates 711A-711R and corresponding binary weighted transistors (-1x, -2x,..., -2R-1x). In the embodiment shown in Figure 36B, each of the equalization registers 704A-704K contains a signed value formed by a coefficient sign (bit S) and a coefficient magnitude (e.g., C1, C2, ..., CK). Referring specifically to equalization register 704A, the coefficient sign is used to select between inverted and non-inverted versions of the data value $Data_j$, while each bit of the coefficient magnitude is input to a logic gate pair. Each logic gate pair consists of an additive and a subtractive logic gate both having a multiplier that corresponds to the bit position of the coefficient magnitude, but with opposite signs. For example, bit 1 of the coefficient magnitude is input to logic gates 712A and 711A which, depending on the state of $Data_{j-1}$, activate the 1x and the -1x transistors, respectively. Similarly, bit 2 of the coefficient magnitude is input to logic gates 712B and 711B to control activation of the 2x

and $-2x$ transistors, and bit R of the coefficient magnitude is input to logic gates 712R and 711R to control activation of the $2R-1x$ and $-2R-1x$ transistors. Although Figure 36B indicates that the coefficient magnitude includes at least three bits (i.e., $R=3$), the coefficient magnitude may include more or fewer than three bits without departing from the scope of the present invention.

Reflecting on the operation of the equalization driver 702A, it can be seen that when the magnitude coefficient in register 704A is zero, all transistors controlled by subtractive logic gates 711A-711R are activated and all transistors controlled by additive logic gates 712A-712R are off. This is true regardless of the state of Dataj-1 or the sign bit, S.

Consequently, when the coefficient magnitude is zero, the equalization current, I_{eq1} is becomes $2R * I_{UNIT}$. When the coefficient magnitude is at a maximum (i.e., all bits set) and Dataj-1 is a logical 1 and the coefficient is positive (i.e., sign bit equal 0), then all the transistors controlled by the subtractive logic gates 711A-711R and all the transistors controlled by the additive logic gates 712A-712R are activated so that the equalization current becomes $2R+1 * I_{UNIT}$. Conversely, when the coefficient magnitude is at a maximum and Dataj-1 is a logical 0 and the coefficient sign is negative, then all the transistors controlled by the subtractive logic gates 711A-711R and all the transistors controlled by the additive logic gates are off so that the equalization current is turned off. More generally, the current I_{EQ1} is given by the expression:

$$I_{EQ1} = 2R * I_{UNIT} + (C1 * 2R) * \text{Polarity}(\text{Dataj-1}) * I_{UNIT},$$

where C1 may be positive or negative and where $\text{Polarity}(\text{Dataj-1}) = 1$ if Dataj-1 is 1; and -1 if Dataj-1 is 0. The currents drawn by equalization circuits 702B-702K are similarly controlled by coefficients C2-CK. By this arrangement, each of the equalization circuits allows current to be increased or decreased relative to $2R * I_{UNIT}$ based on respective coefficients and delayed data values. Thus, the overall current IOL is given by the expression:

$$I_{OL} = I_{SIG} + I_{EQ},$$

$$\begin{aligned} \text{where } I_{EQ} = & 2R * K * I_{UNIT} + C1 * 2R * \text{Polarity}(\text{Dataj-1}) * I_{UNIT} + \\ & C2 * 2R * \text{Polarity}(\text{Dataj-2}) * I_{UNIT} + \\ & \cdot \\ & \cdot \\ & \cdot \\ & CK * 2R * \text{Polarity}(\text{Dataj-k}) * I_{UNIT} \end{aligned}$$

By selecting the current $2R \cdot K \cdot I_{UNIT}$ to correspond to the desired high voltage level on the channel (V_{OH}), the coefficients in the equalization registers can be used to effect a current swing above and below the nominal current used to produce V_{OH} and above and below the nominal current used to produce V_{OL} . These current swings can be used in turn to overdrive or underdrive the channel, compensating the output voltage for past output levels. Note that the current I_{UNIT} drawn by the 1x transistor in the equalization drivers may be different from the current I_{UNIT} drawn by the 1x transistor in the weighted driver 701.

Although Figures 36A and 36B illustrate a pull-down circuit for equalizing the channel voltage, a combination of pull-up and pull-down circuits may be used in an alternative embodiment. For example, a set of weighted transistors coupled between V_{TERM} and the output of driver circuit 700 may be used to pull up the output signal in proportion to a negative equalization coefficient and a corresponding set of weighted transistors may be used to pull down the output signal in proportion to a positive equalization coefficient. Generally, any circuit for adjusting channel voltages may be used without departing from the scope of the present invention.

As mentioned above, cross-talk equalization involves equalizing a channel voltage to compensate for cross-coupled signals from neighboring channels. The circuits shown in Figure 36 and 37 may be modified to provide cross-talk equalization. Referring to Figure 36A, for example, the data history generator 705 may be removed and the outputs of neighboring channels may be coupled to the inputs of equalization drivers 702A-702K. By this arrangement, equalization currents I_{EQ1} - I_{EQK} may be generated based on the state of neighboring channels and weighted by the coefficients stored in equalization registers 704A-704K. As with temporal equalization, a combination of weighted pull-up and pull-down circuits or other circuits for adjusting channel voltages may be used to perform cross-talk equalization. As discussed above, a given device may include both cross-talk equalization circuitry and temporal equalization circuitry.

The foregoing examples of temporal and cross-talk equalization have been drawn to output driver circuit, or transmitter-side circuits. However, such circuit may be incorporated receiver-side.

For example, Figure 37 illustrates a bus receiver 800 with equalization circuitry according to one embodiment of the present invention. Incoming data, $Data_j$, is summed with

an equalization offset 816 in analog adder 817, generating an equalized data value, DEQ, for comparison with VREF. The equalization offset 816 is generated by adding and subtracting equalization coefficients C1-CK according to the state of previously received data values, Dataj-1-Dataj-K, respectively.

5 A data history generator 705 receives the output of comparator 830 and generates the data history values, Dataj-1, Dataj-2, ...Dataj-K. The data history values are used to select, via multiplexers 811A-811K, between positive and negative versions of respective equalization coefficients C1EQ-CKEQ stored in equalization registers 804A-804K. As with the equalization coefficients discussed in reference to Figure 36B, equalization coefficients
10 C1EQ-CKEQ may be positive or negative values. As shown in Figure 37, a negative version of the content of each equalization register 804A-804K is generated by a respective two's-complement generator 809A-809K. Any number of circuits for generating negative versions of the equalization coefficients may be used in alternative embodiments. Also, one's-complement circuitry may be used in alternative embodiments instead of two's complement
15 circuitry.

A digital adding circuit 814 receives the output from each of the multiplexers 811A-811K and provides a sum of coefficients to digital-to-analog converter 815 which generates the equalization offset 816. In an alternative embodiment, separate digital to analog
20 converters are used to convert the outputs of multiplexers 811A-811K to respective analog values. The analog values are then combined with the incoming data value, Dataj, in analog adder 817. In this embodiment, adding stage 814 may be omitted, reducing the amount of time required to provide a valid offset value at adder 817. In another alternative embodiment, adder 817 is used to add the equalization offset 816 to Vref instead of to the incoming data. In this case, the equalization offset is generated with reverse polarity.

25 In yet another embodiment, of the bus receiver, analog rather than digital circuitry is used to perform equalization. Sample and hold circuitry is used to capture past data signals (i.e., Data_{j-1}-Data_k). The amplitude of the captured signals are weighted by equalization coefficients C1_{EQ} - CK_{EQ} from registers 804A-804K, then input to adder 817. Cross-talk equalization is also accomplished in this manner, except that neighboring signals are
30 weighted by the equalization coefficients instead of prior data signals on the same signal path.

Equalization coefficients may be determined using the techniques described above for

determining voltage offset values. See Figures 24 and 29-31 and related discussion above. Referring to the scanning window feedback technique shown in Figure 29, for example, a slave may write a sequence of patterns of successive bits (e.g., 101, 001, 010, 110...) to a master to allow the master to determine the signal margin in the final bit of each pattern. For example, the master may determine that the voltage on the channel is 200mV above VOL in the final bit of the pattern 01 and 200mV below VOH in the final bit of the pattern 10 and provide a coefficient that contributes $\pm 200\text{mV}$ to the slave device.

Thus, by gauging the effect of toggled bits in different positions in the pattern, temporal equalization coefficients may be determined, fed back to the slave and installed in the temporal equalization registers within the slave's transmitter or receiver. Equalization coefficients for the master's transmitter may be determined in a similar manner with the slave returning margin measurements to the master for the master to determine its own coefficients.

In an alternative embodiment, each bit in each equalization register may be set during transmission of the sequence of bit patterns and then reset for transmission of the same sequence. Margin measurements may be made by a receiving device (e.g., a master if a slave's transmitter is being equalized) and used to determine whether the equalization bit should remain set. If the margin is improved, the bit under test is set. Otherwise the bit is reset. By successively testing the effect of each bit in the equalization register, moving from most significant bit to least significant bit, the appropriate equalization value may be determined. Once the content of a given equalization register has been established, the bits in the next register may be tested. Referring to Figure 36A, for example, coefficient C1 may be established first, then coefficient C2, and so forth.

Coefficients for cross-talk equalization may also be determined using the techniques described in reference to Figures 24 and 29-31. However, rather than measuring margins that result from transmission of a given temporal bit pattern, margins are determined based on spatial bit patterns (e.g., different patterns of bits that are transmitted on nearby channels of the bus at the same time, rather than in succession on a single channel). By toggling each of the bit positions in the pattern, spatial coefficients may be determined and installed in the cross-talk equalization registers for the transmitter under test. Also, each bit of each register may be successively determined by comparing margins measured when the bit is set with margins measured when the bit is reset.

Several exemplary techniques have been presented by which timing offsets and voltage offsets and equalization offsets may be determined during the calibration phase of system operation. There are, however, several issues which should be considered when designing reliable and efficient calibration procedures. Definition of an appropriate calibration data sequence is one such issue.

Multiple calibration sequences are possible, but there are few which are optimal. A first preferred sequence consists of very simple 0-to-1 and 1-to-0 transitions at a data rate (frequency) much lower than the normal data rate of the channel during the bus system operation phase. A data rate with a period is larger than the time memory of the channel, e.g., twice the bus electrical length, will usually be adequate. Since the clock and data receivers functioning as phase receivers in the foregoing embodiments are run at normal frequency during the calibration phase, but the data transfer rate is significantly reduced, any timing skews that arise as a function of the data rate are eliminated. In theory, the low frequency data may be considered the mean of the distribution of offsets in a system having frequency dependent offsets. The various offset registers, or rather the offset values stored therein, are determined using this low frequency data and timing, and voltage skews are minimized accordingly.

This approach works because the channel (data bus) transferring data between the master and slaves reacts differently at different data rates. That is, data at different transfer frequencies results in different offsets which are created by resonances and discontinuities at that frequency. Hypothetically, the center of the distribution for such offsets is actually more or less at the same location as the transitions of very low frequency data, such data can be constructed by large data blocks having a single data transition. Such very low frequency data does not excite harmonics the way higher frequency data can, and the single data transition may be readily discerned within the calibration process. Thus, by phase detecting the very low frequency data in receivers running at much higher clock rates, the timing and voltage offsets may be accurately determined.

A second preferred calibration sequence consists of a spectrum of calibration data which starts at a very low frequency and slowly increases until the fundamental is reached. No data frequency is favored over another in this approach, so each frequency is given the same number of data transitions, and thus phase detector evaluations before the frequency is

changed.

In a third preferred calibration sequence, the master observes the valid data window width using the scanning approach explained above, and determines if the communications channel will reliably run at the given frequency. If the master determines that the valid data window is not adequate, it reduces the operating frequency and re-establishes the valid data window width at the new frequency. Since the master's offset registers are calibrated in degrees for most of the foregoing embodiments, the percentage of valid bit-time required for reliable communication can be stored once for all operating frequencies and the final operating frequency need not be an integer multiple of the initial operating frequency.

Preeminent among calibration issues is the fact that data transfers, and in particular control data transfers, between the master and slaves is inherently suspect before completion of the timing and voltage calibration procedures. Figure 38 shows the exemplary bus system of Figure 5 in some different detail. The communication channel between master and slaves, as further illustrated, typically includes a control bus, and a serial data link, in addition to the data bus and external clock signal(s).

As noted, many contemporary bus systems communicate data between the master and slaves in packets. This is particularly true where the bus system comprises a memory system. Thus, the problem of communicating reliable control data from the master to a slave is often compounded by the packet nature of the communicated control data. In yet another aspect, the present invention addresses this problem.

Figure 38 shows the basic configuration of a packet protocol based memory system. In normal operation, the master sends control data over "n" control lines to one or more slave devices. The slaves decode the command indicated by the control data, and perform the requested operation, such as a read or write operation. During a write operation data is transferred from the master to the slave via the data bus and during a read operation data is returned from a slave to the master via the data bus. The control and data packets are sent synchronously relative to the external reference clock, e.g., CTM and CFM. Since in many high performance applications data packets are transferred on both the rising and falling edges of clock signal, the data packets can be viewed as being "even" or "odd" depending on their relationship to the external (EXT.) clock, as illustrated in Figure 39. The system shown in Figure 38 also includes a slow speed serial link typically used during system initialization

to convey device identification.

Many of the timing adjustment circuits explained above and resident in a slave can be functionally summarized by the diagram in Figure 40. An adjusted internal clock, CLKINT (ADJUSTED), is developed and applied to a slave data receiver or transmitter 400. The
5 adjusted internal clock has been derived from an internal clock (CLKINT) typically generated by a clock recovery circuit 401 on the slave receiving the external clock as an input. The internal clock is adjusted by an delay adjustment circuit 402 providing a delay between $-\tau_D$ and $+\tau_D$ in relation to an adjustment value stored in an offset register 403. Within this
10 generalized approach to timing offset compensation, the master will vary the adjustment offset value in the offset register of the slave while performing a sequence of data writes and reads until an optimal offset value is determined which provides the best overall system margin.

Unfortunately, before the receiver and transmitter timing is calibrated to a master clock signal (EXT.CLK), the read and write command packets sent via the control bus may
15 not be received correctly. Unreliable control makes calibration extremely difficult.

To overcome this difficulty the slow speed serial link might be used to send commands to an un-calibrated slave device. However, this solution presents several problems. First, the serial port is very slow. As a result, the calibration process becomes unwieldy and takes an inordinate amount of time. Second, the slave device is forced to
20 multiplex the slow speed read/write commands with normal control and data transfers. This ability requires significant additional control logic. Such additional hardware may delay certain critical paths during normal slave device operation.

Another approach to overcoming the unreliable nature of control packet transfer to un-calibrated slave devices requires that the control command packet be transmitted at half its
25 normal rate. Such a scheme is illustrated in Figure 41. By running at half the normal rate and delaying control data by one quarter cycle, bits on the control bus lines have twice the ordinary timing margin. Such expanded timing margin is sufficient to reliably transfer control data even without calibration of the slave device. Transmitting only the even control bits shifted forward by 90° would provide control data having a similarly expanded timing
30 margin.

While generally superior to transmitting control packets via the serial link, the

foregoing technique presents some challenges to the system designer. The slave device must be capable of responding to two different protocols - one for regular operation and the other for calibration. Several exemplary techniques for accomplishing this result are explained below.

5 Assuming as an example that the slave is a memory device, the control packet typically consists of bit fields representing a number of different components including: a Device ID identifying which slave device is being accessed, an Opcode identifying the nature of the operation, an Address identifying a location related to the operation, and a Write Mask selecting a portion of write data to be stored.

10 During calibration of the memory device not all of these fields are required. For example, if the system has a method of enabling/disabling the memory device through the serial link, which is typical, then the Device ID field is not needed during calibration. All memory devices other than the one being calibrated can be readily disabled using the serial link. The Write Mask need not be use during calibration. Further, only a subset of the
15 normal Opcodes are required during calibration, since the memory device need only perform simple read and write commands. Finally, only a portion of the typical Address field is required. The addressable memory requirements of the memory device during calibration are greatly reduced as compared to normal operation. Accordingly, many of the control packet bits may be utilized for other purposes during calibration.

20 Figure 42 compares the format of a normal operation control packet with the format of a calibration mode control packet. The example assumes a four clock cycle transfer period, a five line control bus, and "normal" odd/even transfer on the rising and falling edges of the clock. In the example "D" bits are Device ID bits, "O" bits are Opcode bits, "ST" are framing bits, "M" bits are Write Mask bits, and "A" bits are Address bits.

25 In the calibration mode data packet, required calibration bits are placed in the odd positions. The even positioned bits effectively become "don't care" bits. This arrangement of bits allows the same overall control packet format and protocol to be used during normal and calibration modes of operation.

30 During calibration, the control packet decode logic will receive correct bits for the odd bits and "don't care" bits for even bits. The logic used to decode control data during normal operation requires remarkably little modification to also decode control data during

calibration. As shown in Figure 43, only the single additional gate and control line, combined 420, need be added to the normal logic.

In the example illustrated by Figures 42 and 43, a serial register bit causes all control packets to be processed, regardless of the state of the control packet D[4:0] bits or the device ID register. As long as the serial register bit is set before calibration starts and the system does not perform any masked writes, the control link will operate reliably with the expanded margins described above.

Restrictions on addressable memory space brought about by the foregoing must be considered when a calibration sequence is defined. Furthermore, as Opcode and Address bits are cannibalized using this approach, the control packet format and the corresponding calibration control logic must also be modified. Such tradeoffs are well within ordinary skill in the art. The foregoing examples of the control packet and its associated decode logic are highly specific to a presently preferred embodiment of the bus system. Any reasonable control packet format, definition of bits, and resulting decoding logic might be used to effect dual operation of the memory device, as between normal operation and calibration, with minimal overhead.

The foregoing embodiments of the present invention illustrate various implementations of the timing and/or voltage control circuitry in the slave devices of an exemplary bus system. However, bus system designers may wish to minimize the size, cost, and complexity of the slave devices. Alternatively, bus system designers may provide a very powerful master device. Whatever the motivation for doing so, the timing and/or voltage control circuits previously described as being resident in individual slave devices may be implemented in the master.

A master incorporating such circuits may generally implement voltage/timing adjustments in one of two ways: a mean control approach or an individual control approach. In the mean control approach, optimizing voltage/timing offsets are calibrated for each slave device during calibration. Once a field of offset values have been calculated, a mean offset value is determined in the master. This mean offset value is stored in a register on the master and used to adjust the read/write timing or the read/write voltage for data being communicated between the master and all slave devices.

In the individual slave device control approach, a separate timing/voltage offset value

is stored in the master for each slave to produce a field of timing/voltage offset values. As described above, an appropriate offset value may be determined for each slave during calibration. Once determined, the offset value is specifically applied to read/write operations involving the corresponding slave.

5 Figure 44 illustrates one example in which current control is implemented for each slave device on an individual basis using offset values stored in the master. As is typical in many contemporary bus systems, this example assumes that each slave device (12a-12n) is identified within the bus system by a unique device ID. Thus, a "request" to access (read/write) data in one slave will include a device ID indicator. The example shows a device
10 ID map circuit 430 receiving a request and extracting a device ID signal from it. The device ID signal is applied to a selector circuit 431, such as a MUX, which also receives a plurality of offset values. Current control registers 432 (CCTLa, CCTLb . . . CCTLn) each contain an offset value for a corresponding slave device (12a, 12b, . . . 12n). A broadcast control register CCTL (BCT) 433 is also provided. The offset value stored in broadcast control register is
15 used by the master when communicating data to all slave devices. This offset value may be the mean control value mentioned above.

 However, in normal operating mode, the device ID extracted from a slave access request is used to select a corresponding current control offset value for the accessed slave device. The selected current control offset value is then applied to a drive circuit 434 which
20 adjusts the current of write signals (control or data) being sent to the slave device. The example shows a single signal line, but one or more drive circuits may adjust the output current on a number of data bus signal lines.

 From this specific example, one of ordinary skill in the art may see that a very similar approach may be taken to implement read signal voltage adjustments in the master. Further,
25 read/write timing adjustments may also be made on the basis of a mean timing offset value or a field of timing offset values stored in the master. Timing control adjustment may be made in relation to a particular offset value by adjusting the master read/write clock signal, or by communicating an slave devices specific internal read/write signal via a signal line.

What is claimed is:

1 1. A bus system comprising a master and a slave connected via a data bus, the master
2 and the slave each receiving a master clock signal, and the slave further comprising:
3 a write offset register storing a write offset value;
4 a receiver receiving data from the data bus in accordance with an internal write clock
5 signal;
6 a receive locked loop circuit generating the internal write clock signal in relation to
7 the master clock signal, wherein the internal write clock varies from the master clock signal
8 in accordance with the write offset value.

1 2. The bus system of claim 1, wherein the slave further comprises:
2 a read offset register storing a read offset value;
3 a transmitter transmitting data onto the data bus in accordance with an internal read
4 clock signal;
5 a transmit locked loop circuit generating the internal read clock signal in relation to
6 the master clock signal, wherein the internal read clock varies from the master clock signal in
7 accordance with the read offset value.

1 3. The bus system of claim 2, wherein the receive locked loop and the transmit locked
2 loop circuits are delay locked loop circuits.

1 4. A bus system comprising:

2 a master and a plurality of N slave devices connected via a data bus, wherein the
3 master communicates data to and from each one of the plurality of N slave devices during a
4 valid data period T;

5 wherein the master and each one of the plurality of N slave devices receives a master
6 clock signal, and

7 wherein each one of the plurality of N slave devices comprises:

8 a receiver receiving data from the data bus upon transition of an internal write clock
9 signal;

10 a transmitter transmitting data onto the data bus upon transition of an internal read
11 clock signal; and

12 a timing adjustment circuit receiving the master clock signal and adjusting the
13 internal write clock signal and the internal read clock signal, such that the transition of the
14 internal write clock signal and the transition of the internal read clock signal occur at the
15 center of period T.

1 5. The bus system of claim 4, wherein the timing adjustment circuit comprises:

2 a clocking circuit receiving the master clock signal and generating the internal write
3 clock signal and the internal read clock signal in relation to the master clock signal;

4 a write offset register connected to the clocking circuit and storing a write offset
5 value, wherein the internal write clock signal is generated in accordance with write offset
6 value; and

7 a read offset register connected to the clocking circuit storing a read offset value,
8 wherein the internal read clock signal is generated in accordance with read offset value.

1 6. The bus system of claim 5, wherein the clocking circuit is a delay locked loop
2 circuit.

1 7. The bus system of claim 5, wherein the master comprises:

2 circuitry capable of individually determining an appropriate read offset value and
3 write offset value for each one of the plurality of N slave devices.

1 8. A bus system comprising:
2 a master and a slave device connected via a data bus, wherein the master
3 communicates data to the slave device during a valid data period T;
4 wherein the slave devices comprises:
5 a receiver receiving data from the data bus upon transition of an internal write clock
6 signal; and,
7 a timing adjustment circuit receiving the master clock signal and adjusting the
8 internal write clock signal such that the transition of the internal write clock signal occur at
9 approximately the center of period T.

1 9. The bus system of claim 8, wherein the timing adjustment circuit further
2 comprises:
3 a delay locked loop (DLL) circuit receiving the master clock signal and generating
4 one or more reference signals;
5 a vector circuit receiving the one or more reference signals and generating a plurality
6 of output signals having different phases;
7 a match delay circuit receiving at least one of the vector circuit output signals and
8 generating the internal write clock signal;
9 a write offset register storing a write offset value;
10 a phase mixer receiving the plurality of output signals from the vector circuit and
11 receiving a signal indicative of the write offset value, and generating a write offset feedback
12 signal applied to the DLL circuit to adjust the internal write clock signal in accordance with
13 the write offset value.

1 10. The bus system of claim 8, wherein the timing adjustment circuit further
2 comprises:

3 a write offset register storing a write offset value;
4 a clocking circuit comprising a receive phase detector circuit receiving the master
5 clock signal, receiving a write offset feedback signal, and generating the internal write clock
6 signal in response to the master clock signal and the write offset feedback signal;
7 a variable delay circuit receiving the internal write clock signal from the clocking
8 circuit and adjusting its delay in accordance with the write offset value to form the write
9 offset feedback signal.

1 11. The bus system of claim 10, wherein the clocking circuit is a delay locked loop,
2 and the variable delay circuit further comprises:

3 a binary weighted chain of inverters variably switched to and from the path of the
4 write offset feedback signal in accordance with the write offset value.

1 12. The bus system of claim 8, wherein the timing adjustment circuit further
2 comprises:

3 a write offset register storing a write offset value;
4 a clocking circuit comprising a receive phase detector circuit receiving a master clock
5 signal, a first write offset feedback signal and a second write offset feedback signal, and
6 generating the internal write clock signal in response to master clock signal and the write
7 offset feedback signal;

8 a first binary weighted chain of current sources controlled by at least a portion of the
9 write offset value and generating the first write offset feedback signal; and

10 a second binary weighted chain of current sources controlled by at least a portion of
11 the write offset value and generating the second write offset feedback signal.

13. The bus system of claim 12, wherein the clocking circuit is a delay locked loop.

1 14. The bus system of claim 8, wherein the timing adjustment circuit further
2 comprises:
3 a write offset register storing a write offset value;
4 a first phase detector receiving a master clock signal and a write offset feedback signal
5 and generating a control signal;
6 a reference loop receiving the master clock signal, generating a plurality of reference
7 signals having different phases, and generating a reference control voltage;
8 an interpolator generating the internal write clock signal in accordance with the
9 control signal received from the first phase detector and the plurality of reference signals
10 received from the reference loop;
11 an internal write clock signal buffer receiving the internal write clock signal from the
12 interpolator; and
13 a write offset feedback signal buffer coupled to the write offset register, receiving the
14 internal write clock signal from the interpolator, and adjusting the delay of the internal write
15 clock signal in accordance with the write offset value to form the write offset feedback signal.

1 15. The bus system of claim 14, wherein the reference loop further comprises:
2 a series of buffers receiving the master clock signal and producing the plurality of
3 reference signals;
4 a second phase detector receiving first and second ones of the plurality of reference
5 signals and generating a pump control signal in response thereto;
6 a charge pump receiving the pump control signal and generating the reference control
7 voltage in accordance with the pump control signal.

1 16. The bus system of claim 8, wherein the timing adjustment circuit further
2 comprises:
3 a write offset register storing a write offset value;
4 a clocking circuit providing reference vectors to a main interpolator and an offset
5 interpolator;
6 wherein the main interpolator generates a write offset feedback signal and the offset
7 interpolator generates the internal write clock signal;
8 a phase detector receiving the write offset feedback signal and the master clock signal
9 and generating an output signal;
10 a main counter receiving the output signal and generating a main counter signal
11 applied to the main interpolator;
12 an adder circuit receiving the main counter signal and a signal indicative of the write
13 offset value and generating an up/down signal;
14 an offset counter receiving the up/down signal and generating an offset counter signal
15 applied to the offset interpolator.

1 17. A bus system comprising a master and a slave connect via a data bus, the slave
2 receiving data from the master via the data bus in a first voltage state and a second voltage
3 state, wherein the difference between the first voltage state and the second voltage state
4 defines a voltage swing, the slave comprising:
5 a write voltage offset circuit storing a write voltage offset value;
6 a write voltage compensating circuit receiving a reference voltage and a signal
7 indicative of the write offset value, and adjusting the voltage swing of the received data such
8 that the first voltage state and the second voltage state are proximately centered about the
9 reference voltage.

1 18. A bus system comprising a master and a slave connect via a data bus, the slave
2 transmitting data to the master via the data bus in a first voltage state and a second voltage
3 state, wherein the difference between the first voltage sate and the second voltage state
4 defines a voltage swing, the slave comprising:

5 a read offset circuit storing a read offset value;

6 a read compensating circuit receiving data to be transmitted to the master and a signal
7 indicative of the read offset value, and adjusting the voltage swing of the transmitted data
8 such that the first voltage state and the second voltage state are proximately centered about a
9 reference voltage.

1 19. The bus system of claim 18, wherein the read compensating circuit receives data
2 to be transmitted to the master and the signal indicative of the read offset value, and adjusts
3 the current of the driver placing the data onto the data bus such that the first voltage state and
4 the second voltage state are proximately centered about a reference voltage.

5 a receiver receiving data from the data bus in accordance with an internal write clock
6 signal;

7 a receive locked loop circuit generating the internal write clock signal in relation to
8 the master clock signal, wherein the internal write clock varies from the master clock signal
9 in accordance with the write offset value.

1 20. A bus system comprising a master and a slave connected via a data bus,
2 the slave comprising:
3 a first clocking circuit receiving a master clock signal;
4 a write offset register storing a write offset value connected to the first clocking
5 circuit;
6 a read offset register storing a read offset value connected to the first clocking circuit;
7 wherein the first clocking circuit generates an internal write clock signal varying in
8 relation to the master clock signal in accordance with the write offset value, and generates an
9 internal read clock signal varying in relation to the master clock signal in accordance with the
10 read offset value;
11 the master comprising:
12 a second clocking circuit capable of generating a normal clock and a calibration
13 shifted clock being shifted 90° from the normal output clock.

1 21. The bus system of claim 20, wherein the first and second clocking circuits are
2 delay locked loop circuits or phase locked loop circuits.

1 22. A method of adjusting read timing and write timing in a slave device receiving
2 data from a master and transmitting data to the master, the method comprising:
3 receiving a master clock signal in the slave device;
4 storing a write offset value and a read offset value;
5 generating an internal read clock signal varying from the master clock signal in
6 accordance with the read offset value, and reading data into the slave device synchronous
7 with the internal read clock signal;
8 generating an internal write clock signal varying from the master clock signal in
9 accordance with the write offset value, and writing data to the master synchronous with the
10 internal write clock signal.

1 23. The method of claim 22, wherein the write offset value is stored in a write offset
2 register in the slave device and wherein the read offset value is stored in a read offset register
3 in the slave device.

1 24. A method of adjusting write timing in a bus system comprising a master
2 connected to a slave device via a data bus, the method comprising:
3 storing a write offset value associated with the slave device;
4 receiving a master clock signal in the slave device;
5 generating an internal write clock signal in relation to the master the clock signal and
6 the write offset value;
7 receiving data from the master synchronous with the internal write clock signal.

1 25. The method of claim 24, wherein the step of generating an internal write clock
2 signal further comprises:
3 generating a plurality of reference signals in a clocking circuit;
4 generating a set of vector signals having different phases using at least one of the
5 plurality of reference signals;
6 outputting one signal from the set of vector signals through a matched delay as the
7 internal write clock signal;
8 generating a write offset feedback signal to the clocking circuit in relation to a signal
9 indicative of the write offset value and the set of vector signals.

1 26. The method of claim 25, wherein the clocking circuit comprises a delay locked
2 loop;

1 27. The method of claim 26, wherein the step of generating a write offset feedback
2 signal is performed in a phase mixer receiving the signal indicative of the write offset value
3 and the set of vector signals.

1 28. The method of claim 24, wherein the step of generating an internal write clock
2 signal further comprises:
3 receiving a master clock signal and a write offset feedback signal in a clocking circuit
4 phase detector;
5 generating the internal write clock signal in the clocking circuit;
6 generating the write offset feedback signal in accordance with the write offset value.

1 29. The method of claim 28, wherein the step of generating the write offset feedback
2 signal further comprises:
3 applying the internal write clock signal to a variable delay circuit; and,
4 adjusting the delay of the internal write clock signal in the variable delay circuit in
5 accordance with the write offset value to generate the write offset feedback signal.

1 30. The method of claim 24, wherein the step of generating an internal write clock
2 signal further comprises:
3 applying at least a portion of the write offset value to a first binary weighted chain of
4 current sources and a second binary weighted chain of current sources to generate
5 respectively first and second write offset feedback signal;
6 applying the first and second write offset feedback signals to a clocking circuit phase
7 detector circuit to generate the internal write clock signal.

1 31. The method of claim 24, wherein the step of generating an internal write clock
2 signal further comprises:

3 receiving a master clock signal and a write offset feedback signal in a phase detector
4 and generating a control signal;

5 generating a plurality of reference signals having different phases in a reference loop
6 receiving the master clock signal;

7 generating a reference control voltage in the reference loop;

8 generating the internal write clock signal in an interpolator in accordance with the
9 control signal and the plurality of reference signals;

10 applying the internal write clock signal to an internal write clock signal buffer and to
11 a write offset feedback signal buffer; and

12 adjusting the delay of the internal write clock signal in the write offset feedback signal
13 buffer in accordance with the write offset value to form the write offset feedback signal.

1 32. The method of claim 24, wherein the step of generating an internal write clock
2 signal further comprises:

3 applying phased reference vectors from a delay locked loop circuit to parallel first and
4 second interpolators, the first interpolator generating the internal write clock signal and the
5 second interpolator functioning in a feedback loop providing a write offset feedback signal to
6 the first interpolator;

7 adjusted the write offset feedback signal in the feedback loop using the write offset
8 value.

1 33. The method of claim 24, wherein the step of generating an internal write clock
2 signal further comprises:
3 applying a plurality of reference vectors received from a clocking circuit to a main
4 interpolator and a offset interpolator;
5 generates a write offset feedback signal in the main interpolator;
6 generating the internal write clock signal in the offset interpolator;
7 applying the write offset feedback signal and the master clock signal to a phase
8 detector and generating an output signal;
9 applying the output signal to a main counter and generating a main counter signal;
10 applying the main counter signal to the main interpolator;
11 applying the main counter signal and a signal indicative of the write offset value to an
12 adder circuit and generating an up/down signal;
13 applying the up/down signal to an offset counter and generating an offset counter
14 signal;
15 applied the offset counter signal to the offset interpolator.

1 34. A method of adjusting a voltage swing for data in a bus system comprising a
2 master connected to a plurality of slaves via a data bus, the method comprising:
3 for each slave in the plurality of slaves, individually,
4 storing an input voltage offset value in a register on the slave;
5 receiving data at the slave from the master via the data bus;
6 adjusting the voltage swing of the received data in accordance with the input voltage
7 offset value.

1 35. A method of adjusting a voltage swing for data in a bus system comprising a
2 master connected to a plurality of slaves via a data bus, the method comprising:
3 for each slave in the plurality of slaves, individually,
4 storing a driver current offset value in a register on the slave;
5 adjusting output current for a data driver in the slave in accordance with the driver
6 current offset value.

1 36. A method of adjusting a data voltage levels in a bus system comprising a master
2 connected to a plurality of slave devices via a data bus, the method comprising:
3 individually determining for each slave device in the plurality of slave devices at least
4 one voltage offset;
5 within each slave device, applying the at least one individually determined voltage
6 offset to the data voltage levels data received from the master via the data bus.

1 37. The method of claim 36, wherein the at least one voltage offset for each slave
2 device is determined in relation to a reference voltage.

1 38. The method of claim 37, wherein the reference voltage is externally generated
2 from the slave device.

1 39. The method of claim 36, wherein the step of individually determining for each
2 slave device in the plurality of slave devices at least one voltage offset, further comprises:
3 for each slave device, scanning the data voltage levels for data received from the
4 master to determine upper and lower failure points and determining the at least one voltage
5 offset in relation to the upper and lower failure points.

1 40. A method of determining a compensating voltage offset applied to data received
2 by a slave device from a master via a data bus in a bus system in which a reference voltage is
3 normally communicated from the master to the slave via a reference voltage signal line, the
4 method comprising:

5 communicating a test voltage signal from the master to the slave via one or more
6 signal lines of the data bus;

7 applying the test voltage signal to the reference voltage signal line;

8 comparing in the slave device the level of the test voltage signal on the one or more
9 signal lines of the data bus with the level of test voltage signal on the reference voltage signal
10 line;

11 determining the compensating voltage offset in relation to the comparison of test
12 voltage signal levels.

1 41. A method of determining a compensating drive current offset for a slave device
2 transmitting data to a master via a data bus, the method comprising:
3 driving data onto the data bus at the slave device;
4 receiving the data at the master in a comparator circuit and comparing the voltage
5 level of the data to a reference voltage;
6 generating an up/down signal on the basis of the comparison between the data voltage
7 level and the reference voltage;
8 communicating the up/down signal from the master to the slave device;
9 adjusting a value in current control register in relation to the up/down signal, wherein
10 the value in the current control register defines the drive current offset for the slave device.

1 42. The method of claim 41, wherein the step of driving data onto the data bus further
2 comprises:
3 driving a high data value on a first signal line of the data bus and driving a low data
4 value on a second signal line of the data bus; and,
5 wherein the comparator circuit further comprises:
6 a precision resistor divider switched between the first and second signal lines.

1 43. A method of determining a timing adjustment offset for a slave device receiving
2 data from a master via a data bus, the method comprising:
3 shifting the transmit clock in the master by 90°;
4 outputting a calibration data sequence from the master;
5 adjusting an internal write clock in the slave device to determine the center point for a
6 data transition period defined by the shifted master transmit clock; and
7 determining the timing adjustment offset in relation to the determination of the center
8 point for the data transition period.

1 44. The method of claim 43, wherein the internal write clock is adjusted by
2 incrementing or decrementing a value stored in an write offset register in the slave device.

1 45. The method of claim 44, wherein the step of adjusting an internal write clock in
2 the slave device to determine the center point for a data transition period defined by the
3 shifted master transmit clock, further comprises:

4 (a) adjusting the internal write clock and reading the data received from the master;

5 (b) decrementing the value of the write offset register when a high data value is read
6 or incrementing the value of the offset register when a low data value is read;

7 (c) continuing steps (a) and (b) until such time as the value of the write offset register
8 toggles with each successive adjustment of the internal write clock.

1 46. The method of claim 43, wherein the calibration data sequence comprises a
2 relatively large data block having a single data transition between a high data value and a low
3 data value.

1 47. A method of determining a timing adjustment offset for a slave device
2 transmitting data to a master via a data bus, the method comprising:

3 shifting the receive clock in the master by 90°;

4 outputting a calibration data sequence from the slave device;

5 using a receiver in the master as a phase detector, determining the center point for a
6 data transition period defined by an internal read clock in the slave device; and

7 determining the timing adjustment offset for the internal read clock in relation to the
8 determination of the center point for the data transition period.

1 48. The method of claim 47, wherein the internal read clock is adjusted by
2 incrementing or decrementing a value stored in an read offset register in the slave device.

1 49. A method of determining a timing adjustment offset for a slave device internal
2 write clock in relation to a data eye defined by a master transmit clock, the method
3 comprising:

4 scanning a sample clock signal across the breadth of the data eye to determine a
5 leading and a lagging edge of the data eye;

6 defining a timing adjustment offset for the slave device internal write clock in relation
7 to the determination of the leading and lagging edges of the data eye.

1 50. The method of claim 49, wherein the step of scanning of the sample clock is
2 performed by at least one offset interpolator.

1 51. The method of claim 50, wherein the step of scanning the sample clock further
2 comprises:

3 (a) reading a specific offset value from a range of offset values stored in a register;

4 (b) applying the specific offset value to the at least one offset interpolator;

5 (c) repeating steps (a) and (b) until the leading and lagging edges of the data eye have
6 been determined.

1 52. A method of communicating control information in a bus system comprising a
2 master connected to a slave via a bus, the method comprising:

3 during normal operation of the bus system following calibration, communicating
4 control information from the master to the slave in normal packets having a first period;

5 during calibration of the bus system, communicating control information from the
6 master to the slave in calibration packets having a second period greater than the first period.

1 53. The method of claim 52, wherein the normal packets are arranged as even packets
2 sent from the master to the slave on the rising edge of a master clock and odd packets sent
3 from the master to the slave on the falling edge of the master clock.

1 54. The method of claim 53, wherein the second period is twice as long as the first
2 period.

1 55. The method of claim 54, wherein a normal packet is sent from the master to the
2 slave in alternating even and odd packets over a number of master clock cycles.

1 56. The method of claim 55, wherein the calibration packet is sent from the master to
2 the slave in even and odd packets over the number of master clock cycles, where control
3 information contained in the even packets is duplicated in the odd packets.

1 57. A method of communicating control information in a bus system comprising a
2 master connected to a slave via a bus, the method comprising:
3 during normal operation of the bus system following calibration, communicating
4 control information from the master to the slave in normal packets having a first period and
5 having a normal packet format;
6 during calibration of the bus system, communicating control information from the
7 master to the slave in calibration packets having a second period twice the first period and
8 having a calibration packet format.

1 58. The method of claim 57, wherein the calibration packet format allows fewer
2 opcodes definitions than the normal packet format.

1 59. The method of claim 57, wherein the calibration packet format contains fewer
2 write mask bits than the normal packet format.

1 60. The method of claim 57, wherein the calibration packet format contains fewer
2 address bits than the normal packet format.

1 61. The method of claim 57, wherein the calibration packets are communicated via a
2 slow speed serial link between the master and slave device.

1 62. A bus system comprising a master and a plurality of slaves connected via a data
2 bus, the master comprising:

3 means for determining a plurality of offset values, each one of the plurality of offset
4 values corresponding to one of the plurality of slaves;

5 at least one circuit storing the plurality of offset values; and,

6 a selection circuit selecting one of the plurality of offset values.

1 63. The bus system of claim 62, wherein each one of the plurality of slaves is
2 identified within the bus system by a unique device ID, the bus system further comprising:

3 a circuit extracting a device ID from an access request;

4 wherein the selection circuit receives the device ID and selects the one offset value in
5 response thereto.

1 64. The bus system of claim 63, wherein the offset value comprises one selected from
2 a group consisting of:

3 a current control offset adjusting a current level for write signals sent from the master
4 to the slave;

5 a read voltage control offset adjusting a voltage level for read signals sent from the
6 slave to the master;

7 a read timing control offset adjusting a read clock; and,

8 a write timing control offset adjusting a write clock.

1 65. A method of adjusting read/write timing in a bus system comprising a master and
2 a plurality of slaves, the method comprising:

3 determining a timing offset value for each slave in relation to a master clock signal to
4 produce a field of slave timing offset values;

5 determining a mean timing offset value from the field of slave timing offset values;
6 and

7 adjusting read/write timing in the bus system in relation to the mean timing offset
8 value.

1 66. A method of adjusting signal voltage in a bus system comprising a master and a
2 plurality of slaves, the method comprising:

3 determining a voltage offset value for each slave in relation to a reference voltage
4 signal to produce a field of slave voltage offset values;

5 determining a mean voltage offset value from the field of slave voltage offset values;
6 and

7 adjusting read/write signal voltages in the bus system in relation to the mean voltage
8 offset value.

1 67. A method of adjusting signal voltage in a bus system comprising a master and a
2 plurality of slaves, the method comprising:

3 determining a voltage offset value for each slave in relation to a reference voltage
4 signal to produce a field of slave voltage offset values;

5 storing the field of slave voltage offset values in the master; and

6 individually adjusting read/write signal voltages for signals communicated between
7 the master and each one of the plurality of slaves on the basis of a selected one of the field of
8 slave voltage offset values.

1 68. The method of claim 68, wherein one of the field of slave voltage offset values is
2 selected on the basis of a unique slave device ID extracted from an access directed to the
3 slave.

1 69. A method of adjusting write signal timing in a bus system comprising a master
2 and a plurality of slaves, the method comprising:

3 determining a write signal offset value for each slave in relation to a master clock
4 signal to produce a field of slave write signal offset values;

5 storing the field of slave write signal offset values in the master; and

6 individually adjusting write timing for signals communicated from the master to each
7 one of the plurality of slaves on the basis of a selected one of the field of slave write signal
8 timing offset values.

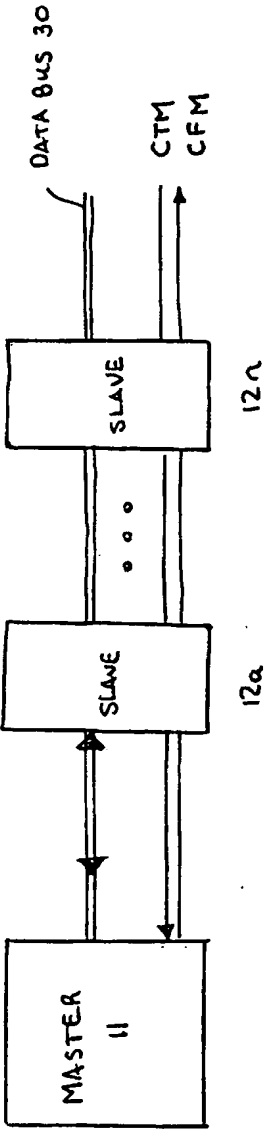


Figure 1

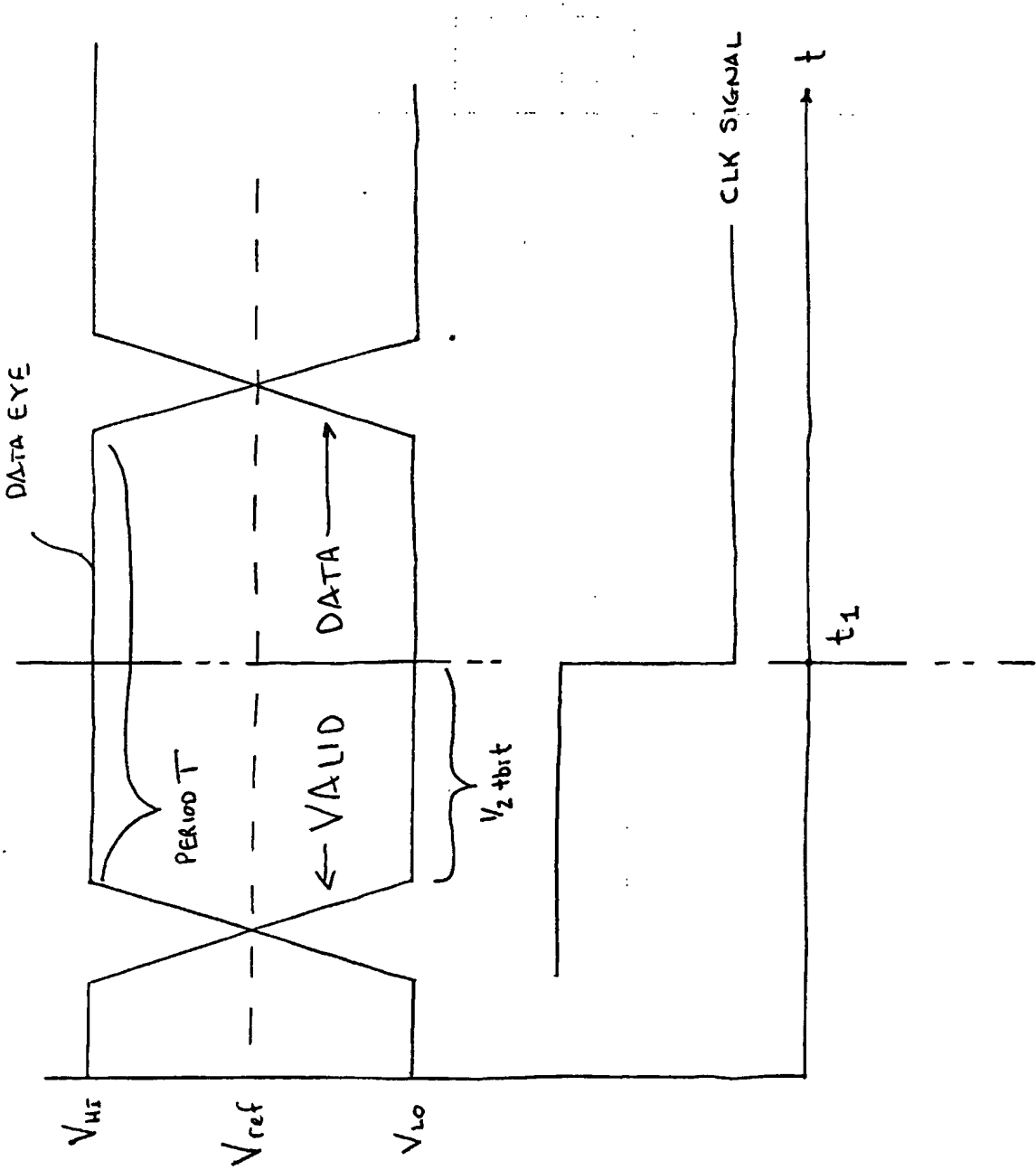


Figure 2

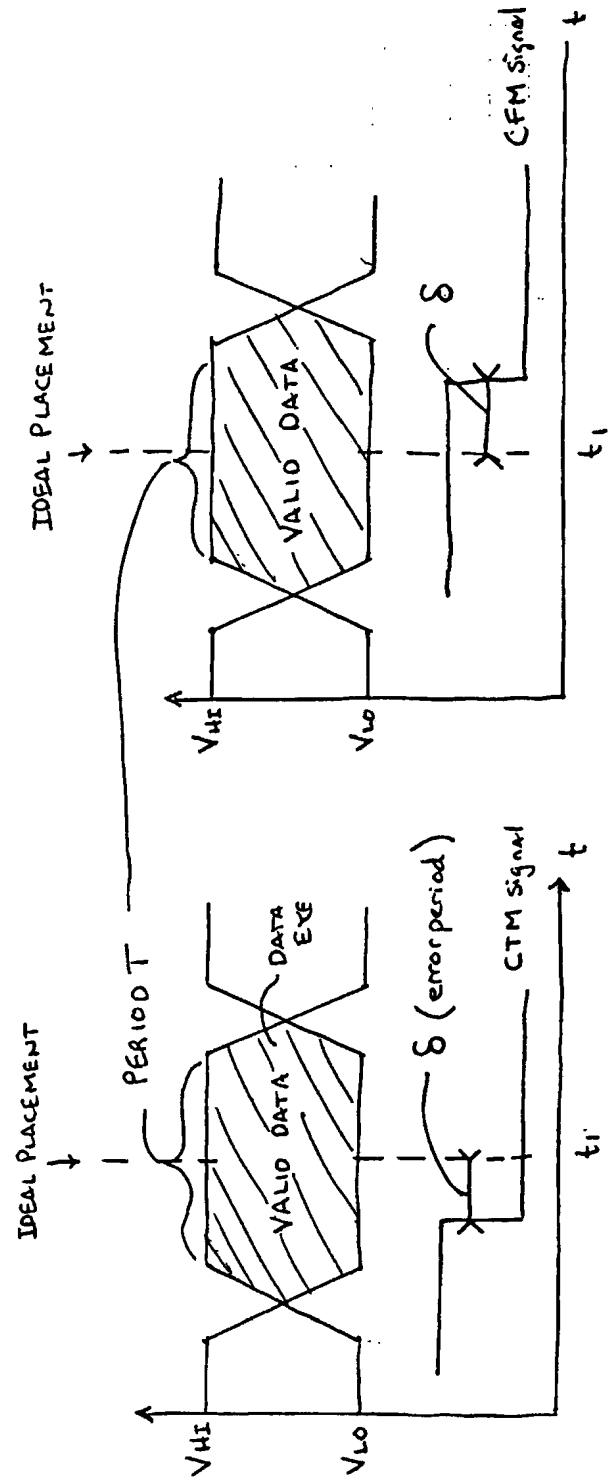


Figure 3A

Figure 3B

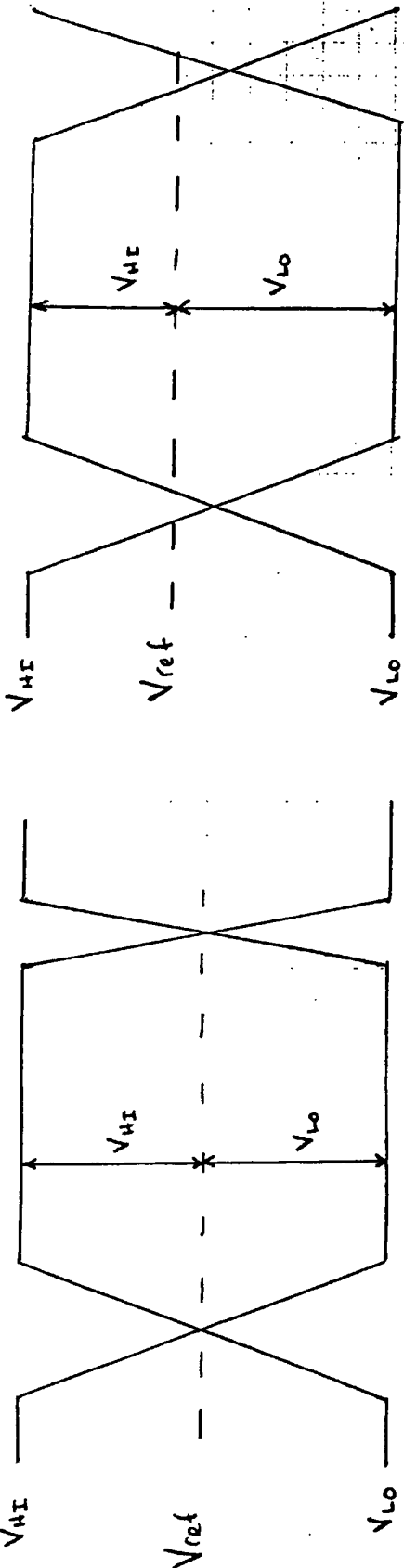


Figure 4A

Figure 4B

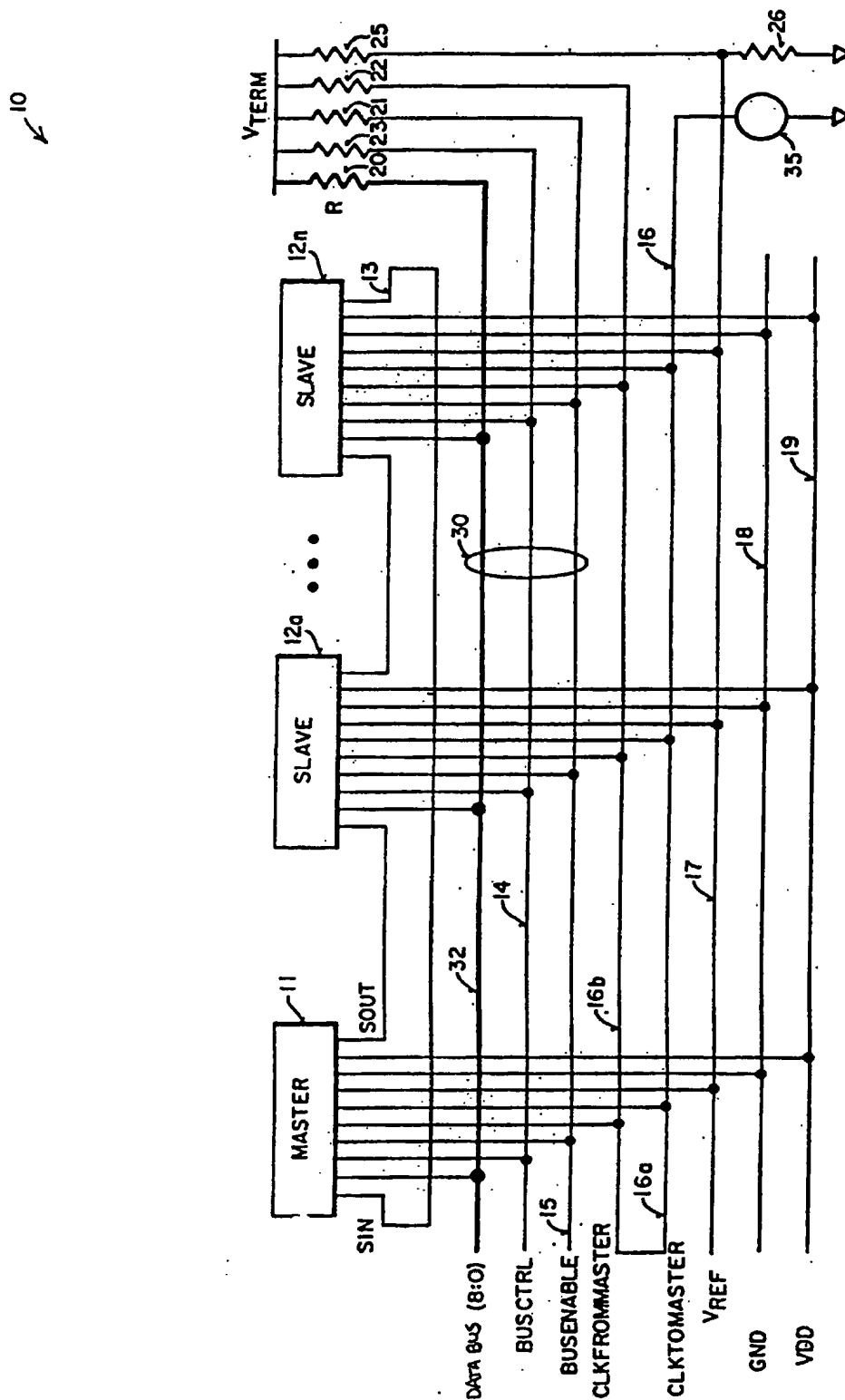


Figure 5

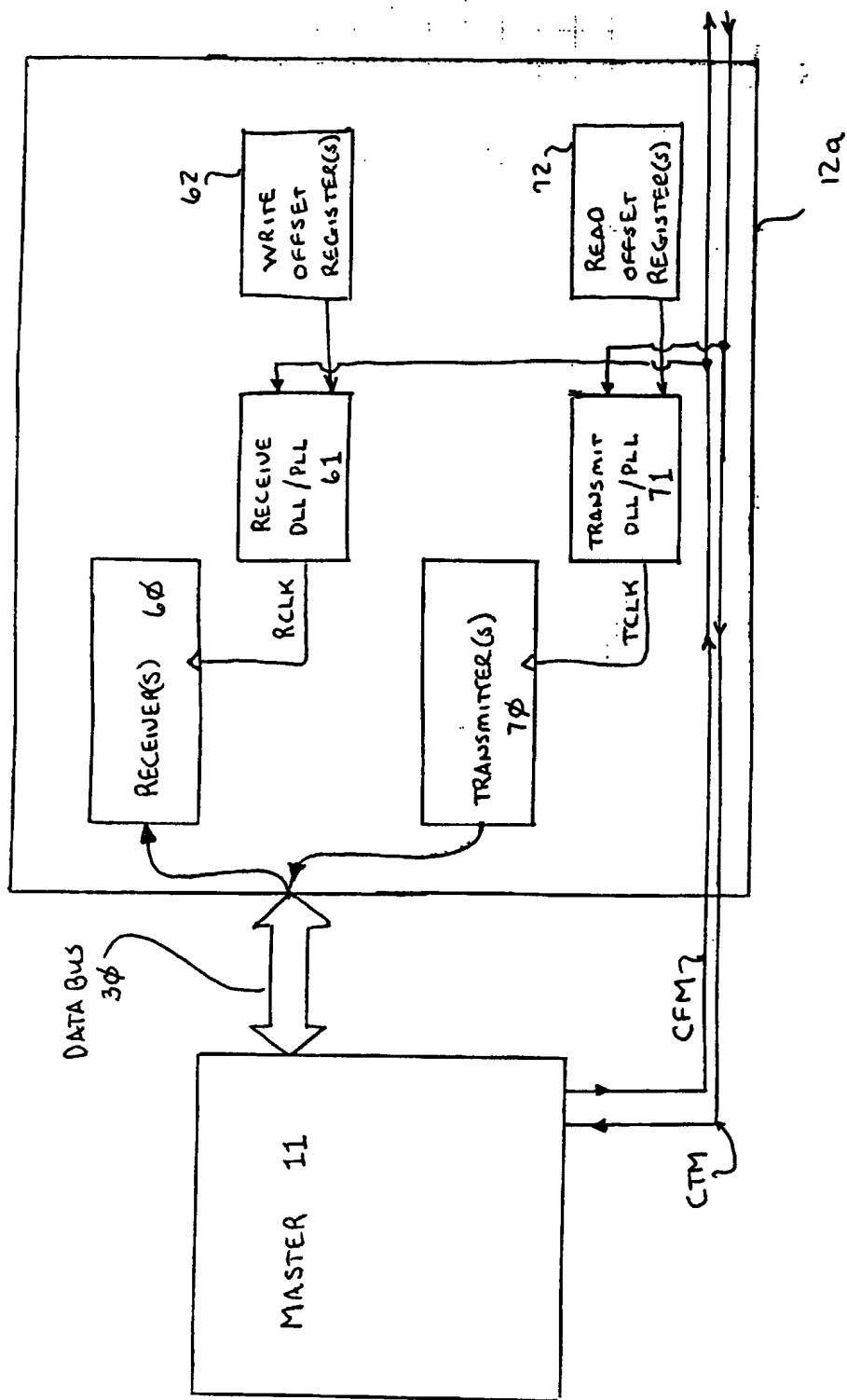


Figure 6

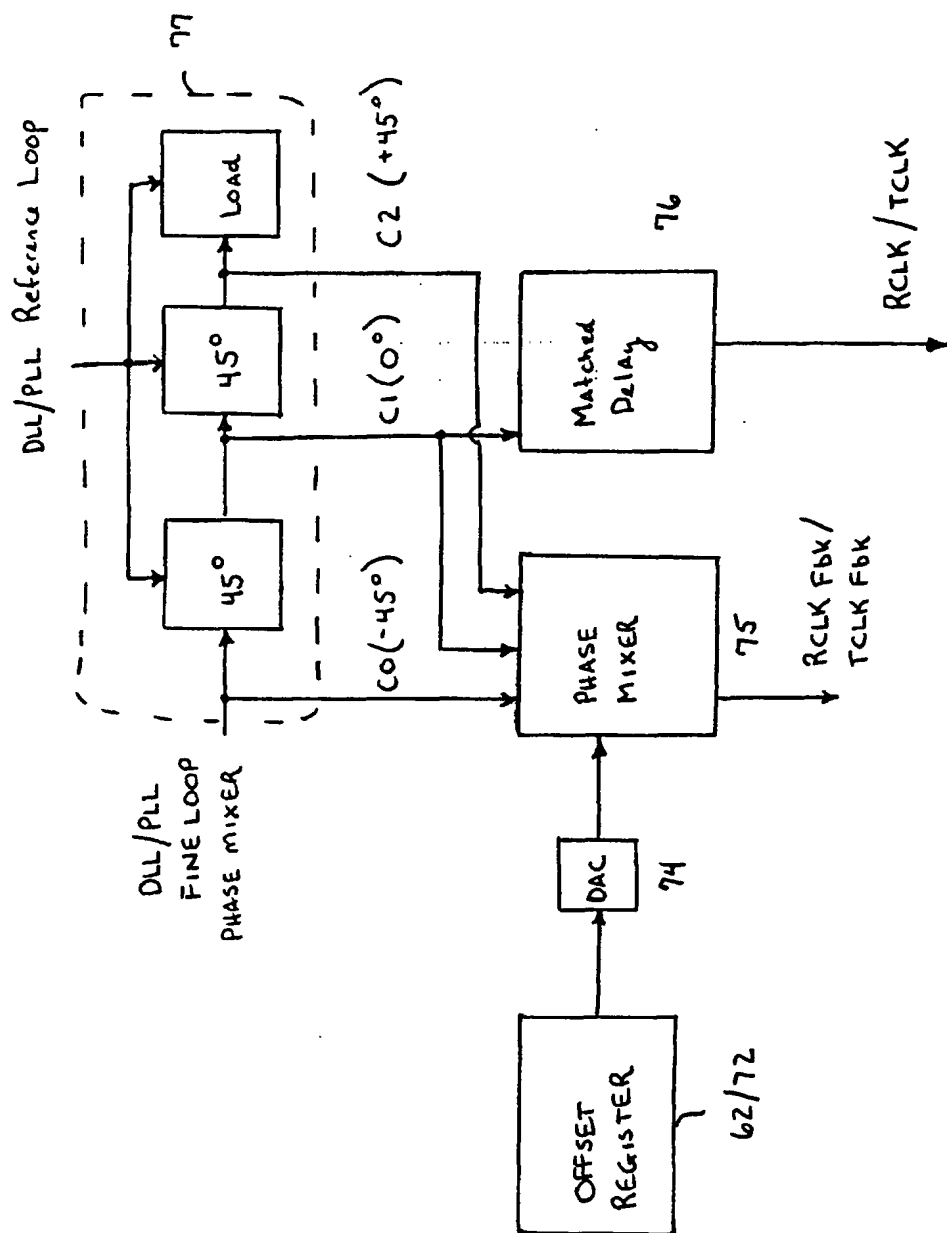


Figure 7

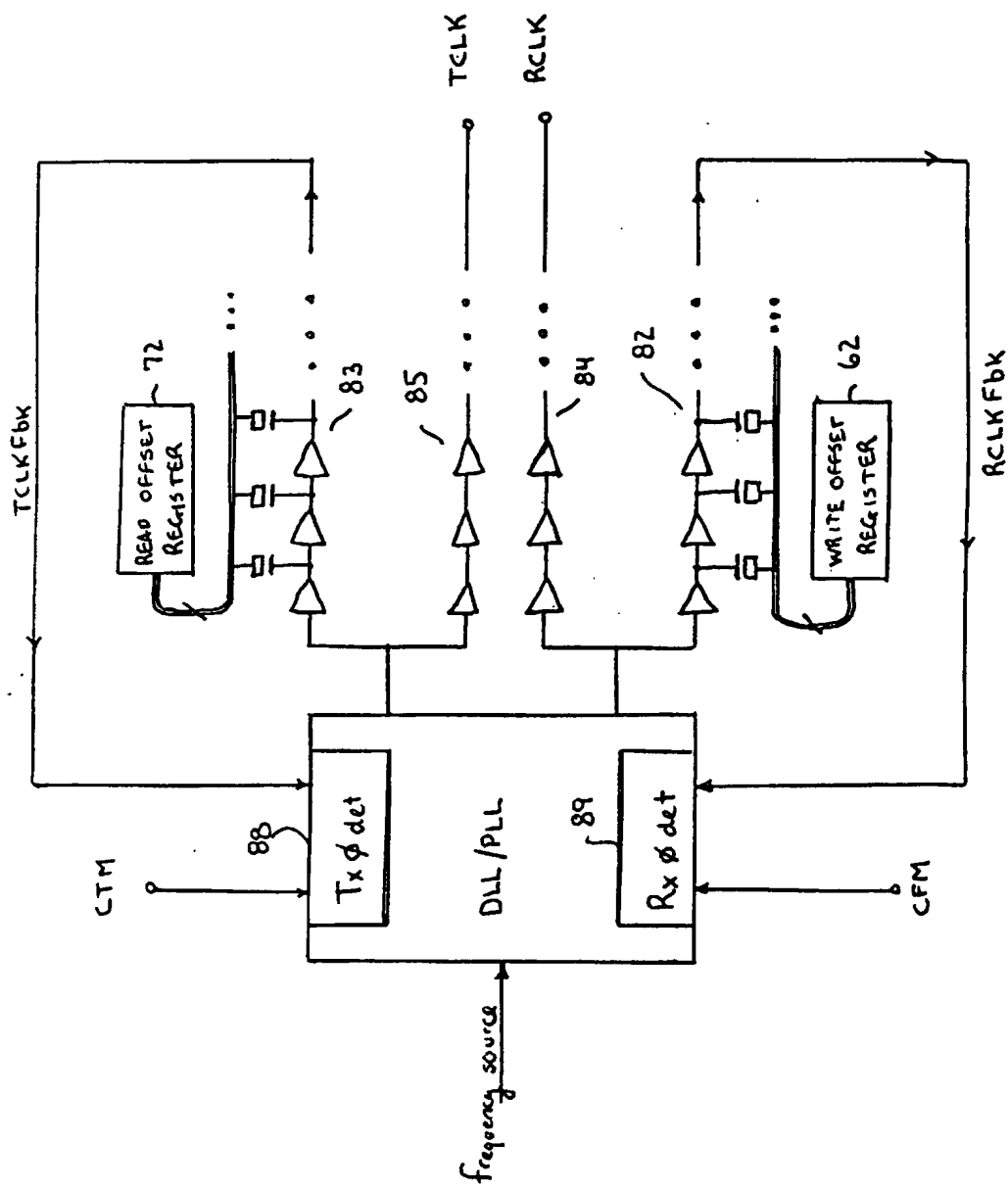


Figure 8

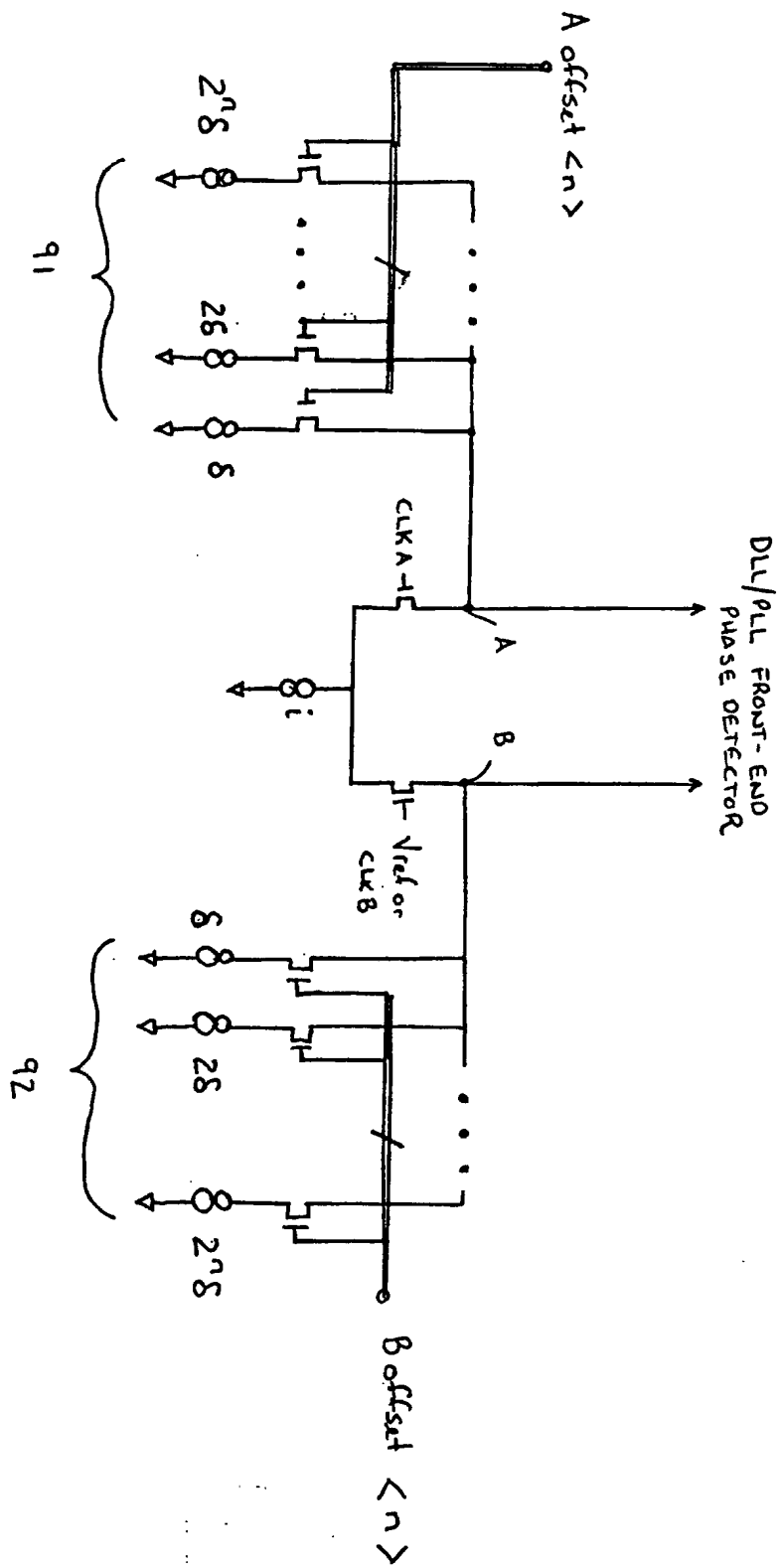


Figure 9

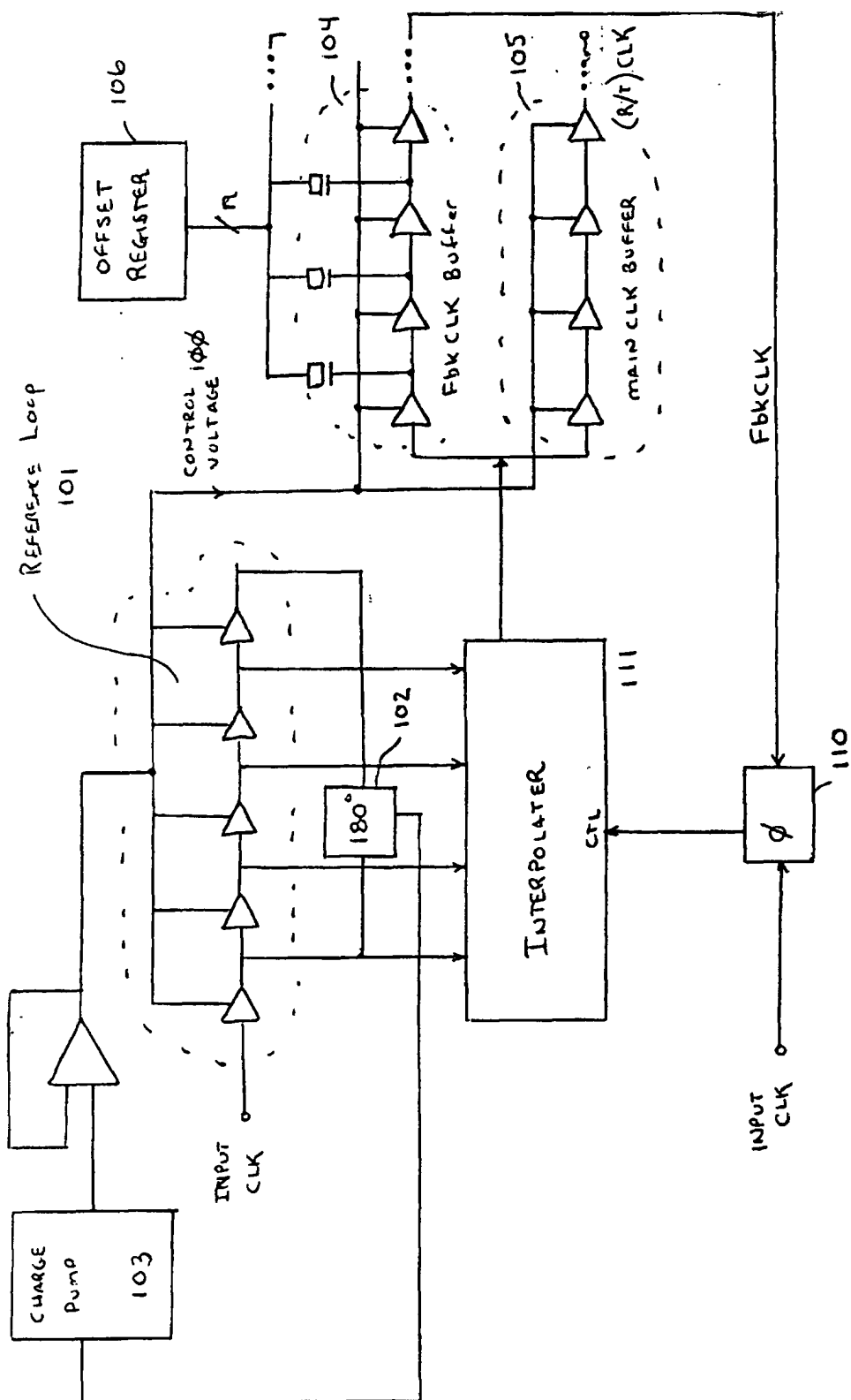


Figure 10

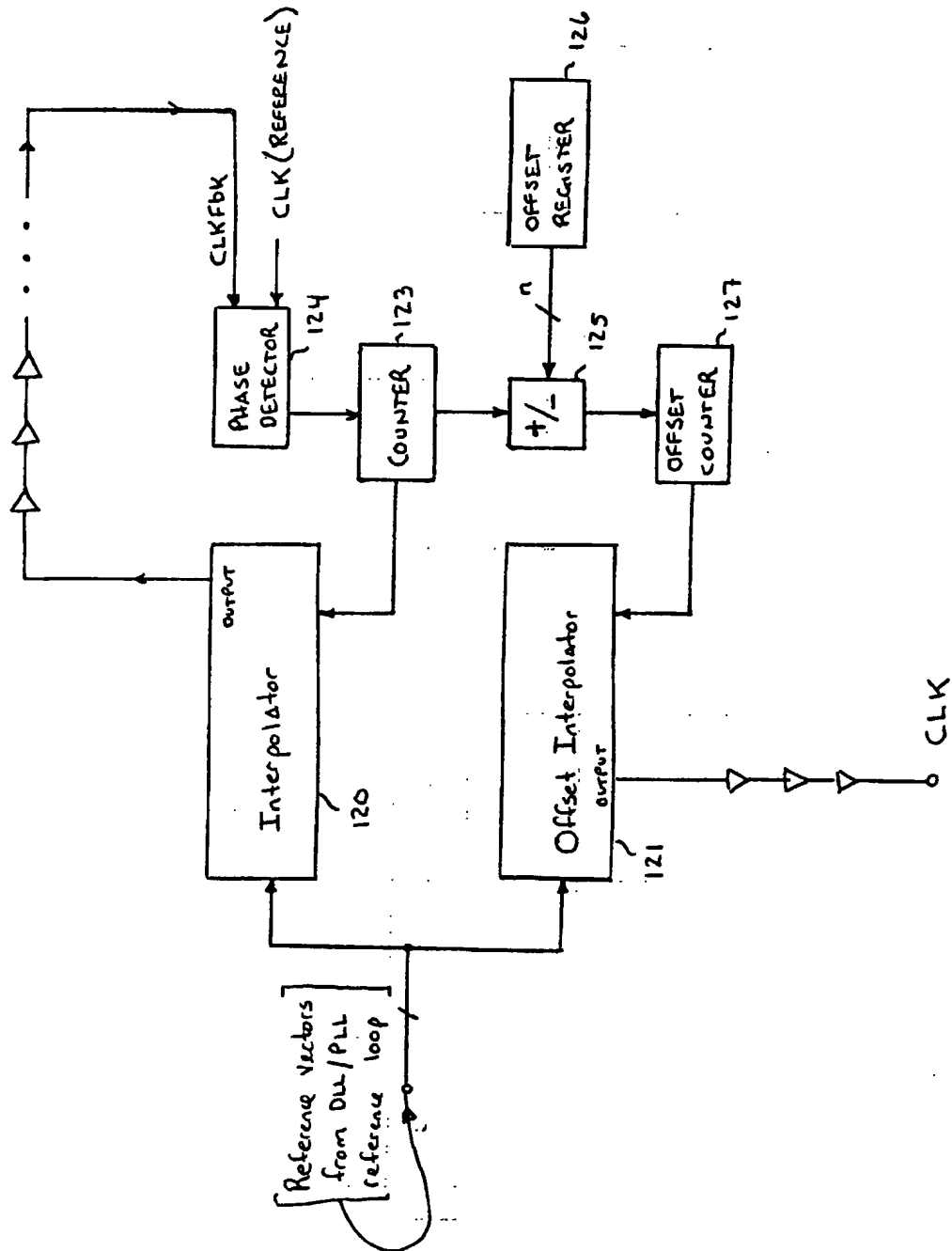


Figure 11

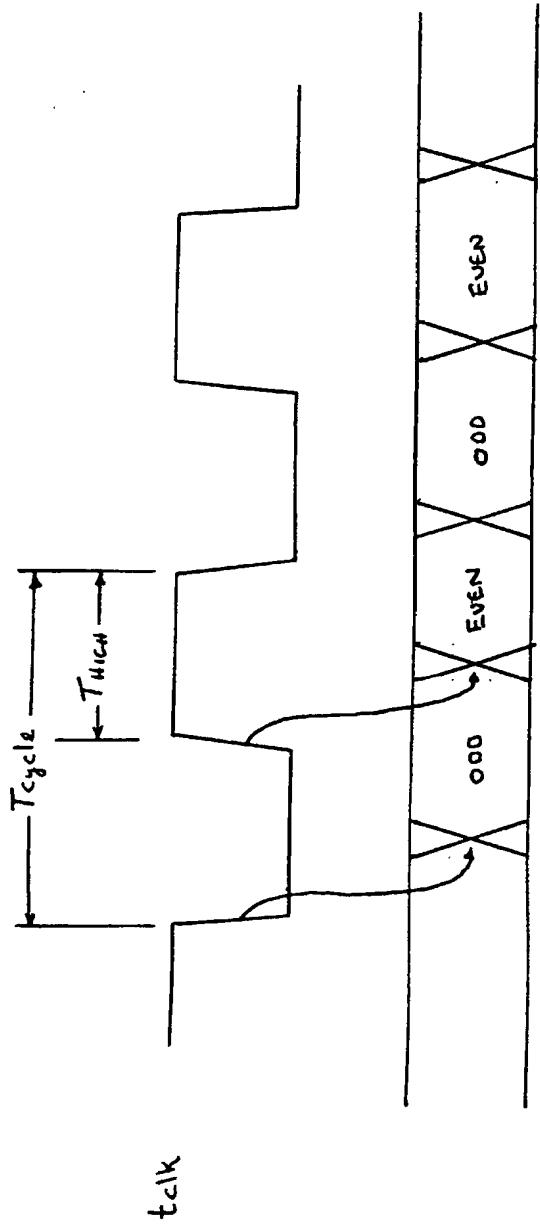


Figure 12A

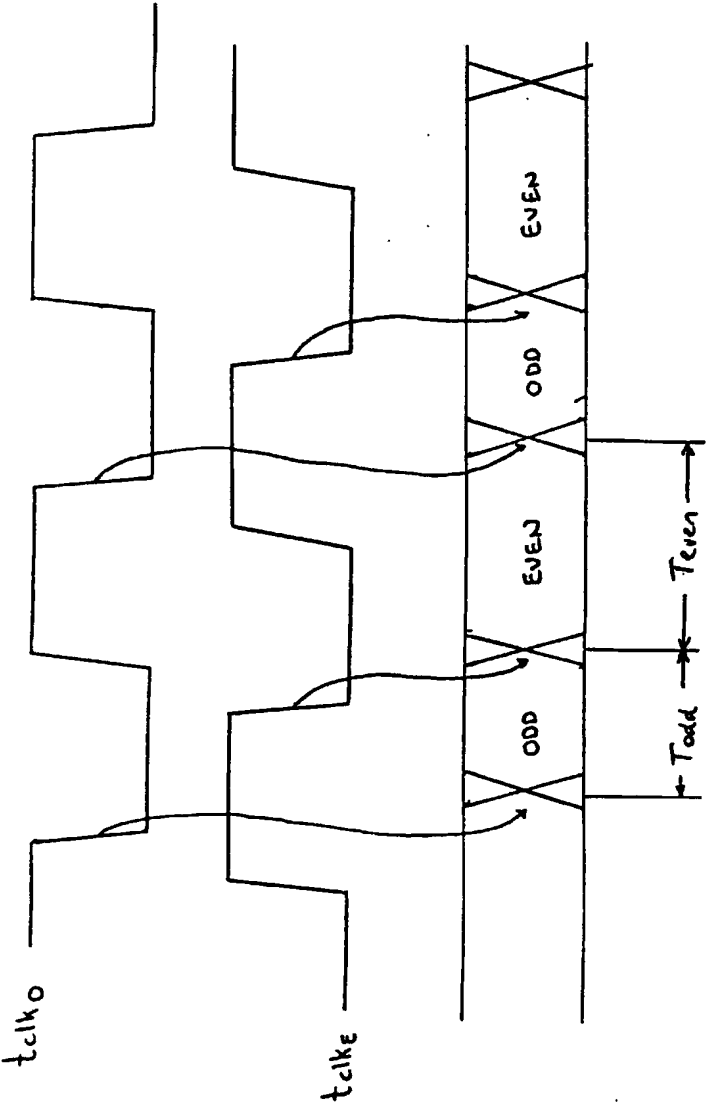


Figure 12B

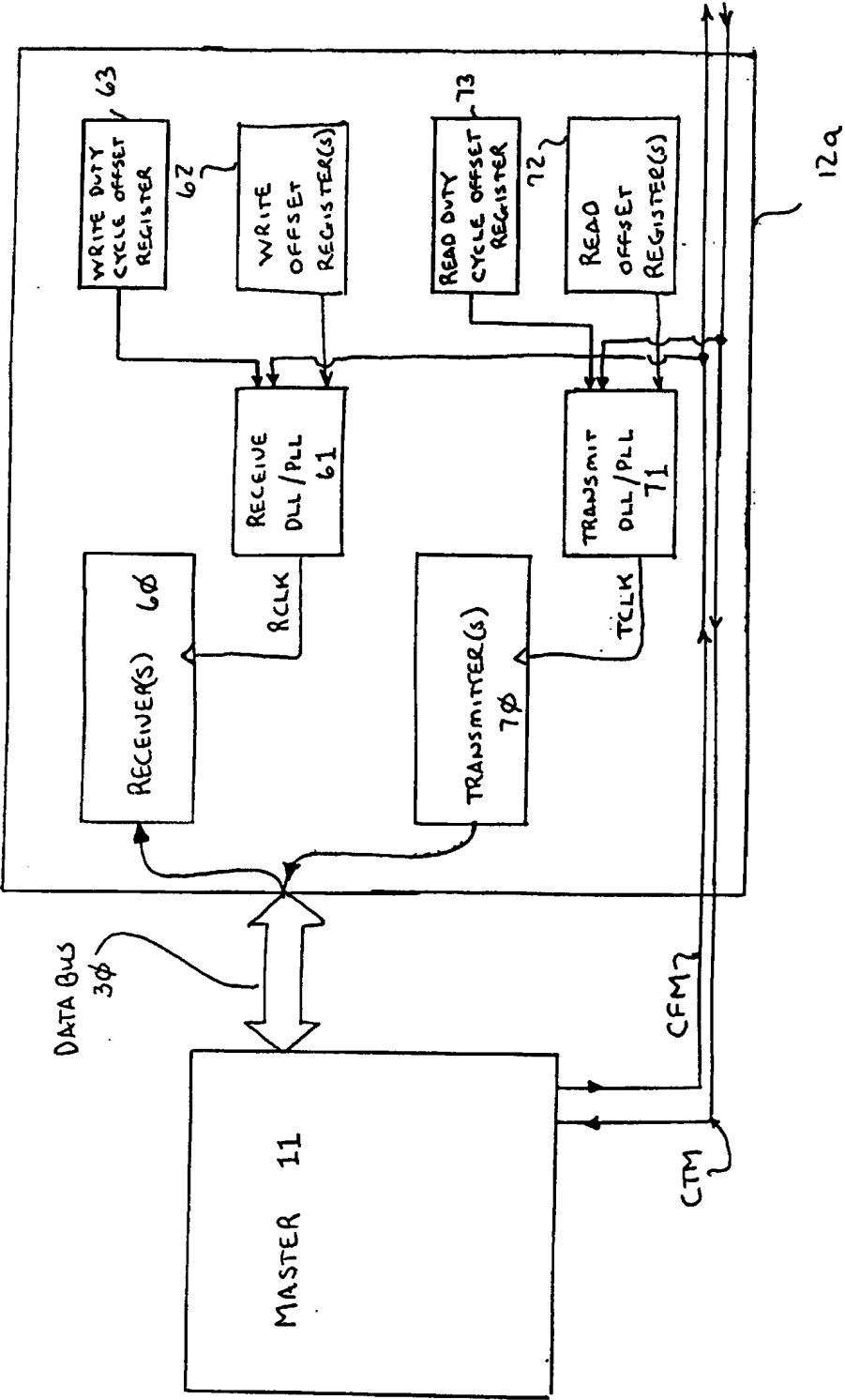


Figure 13

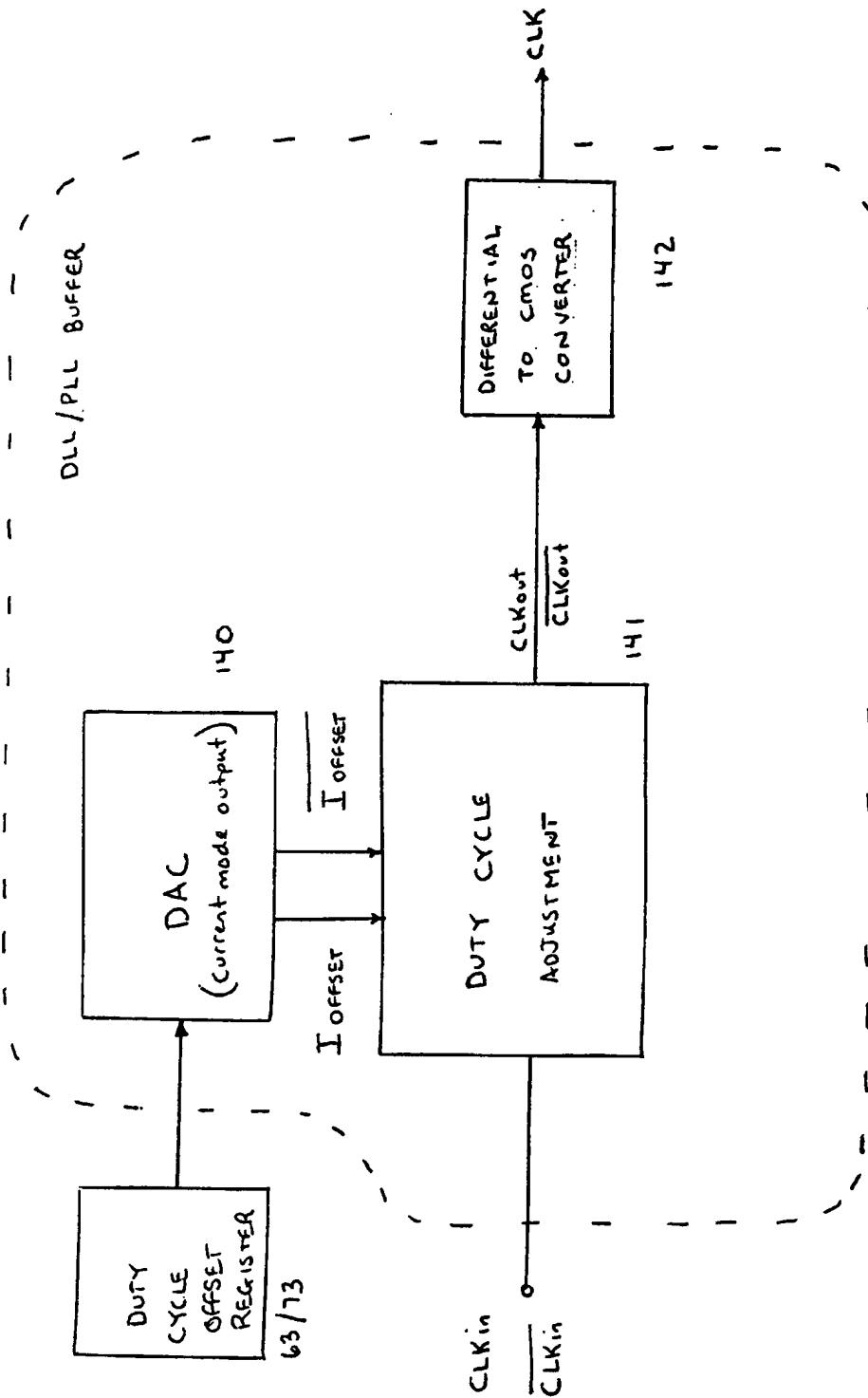


Figure 14

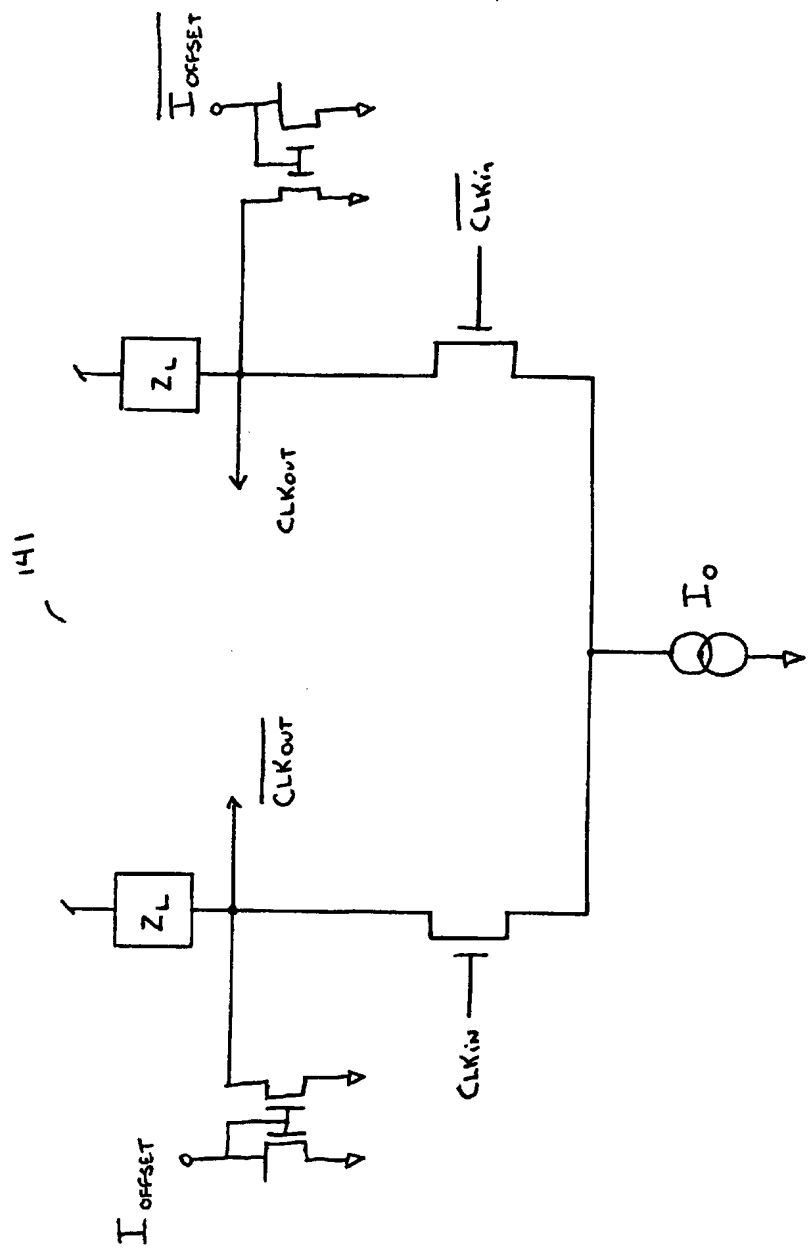


Figure 15

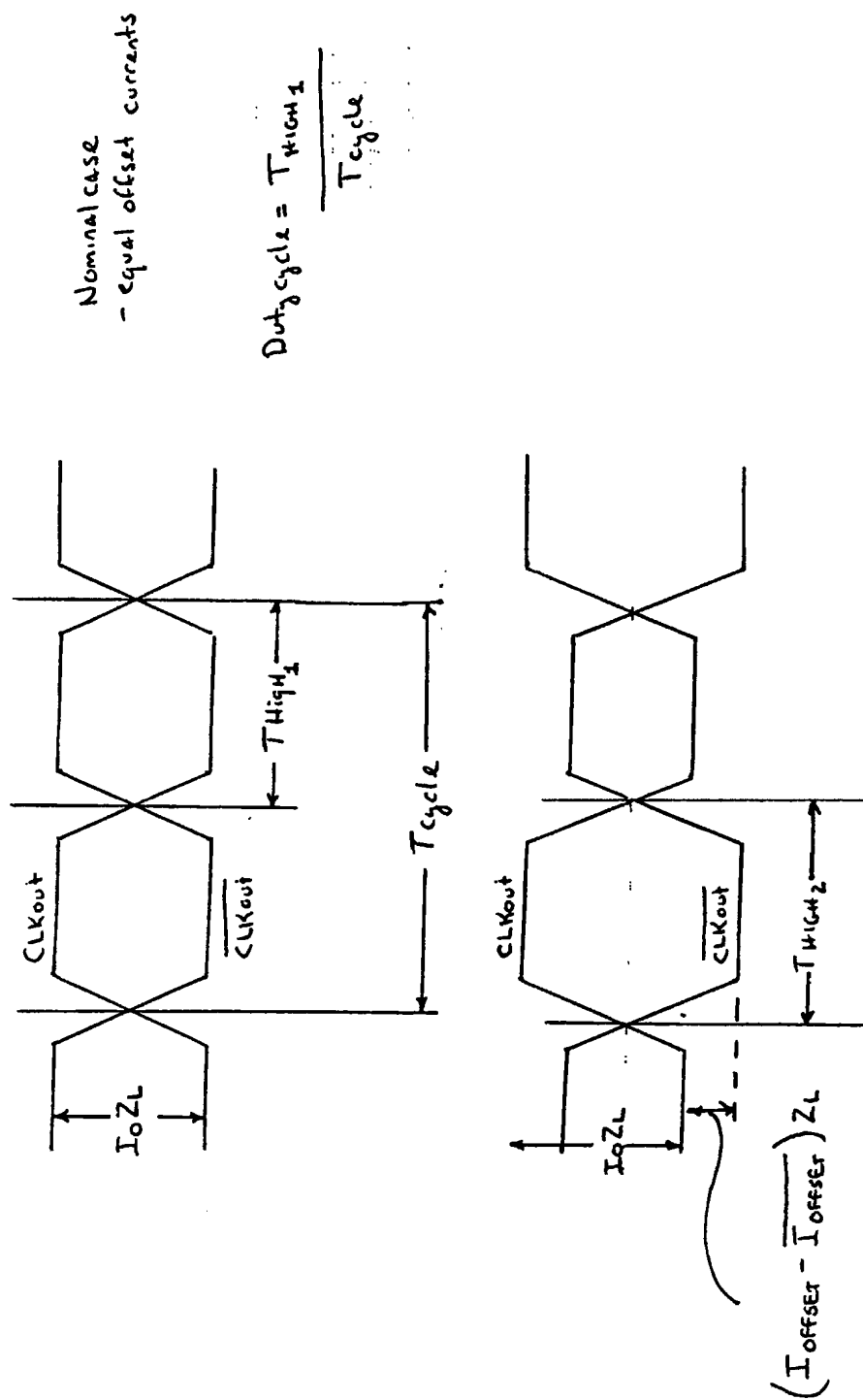


Figure 16

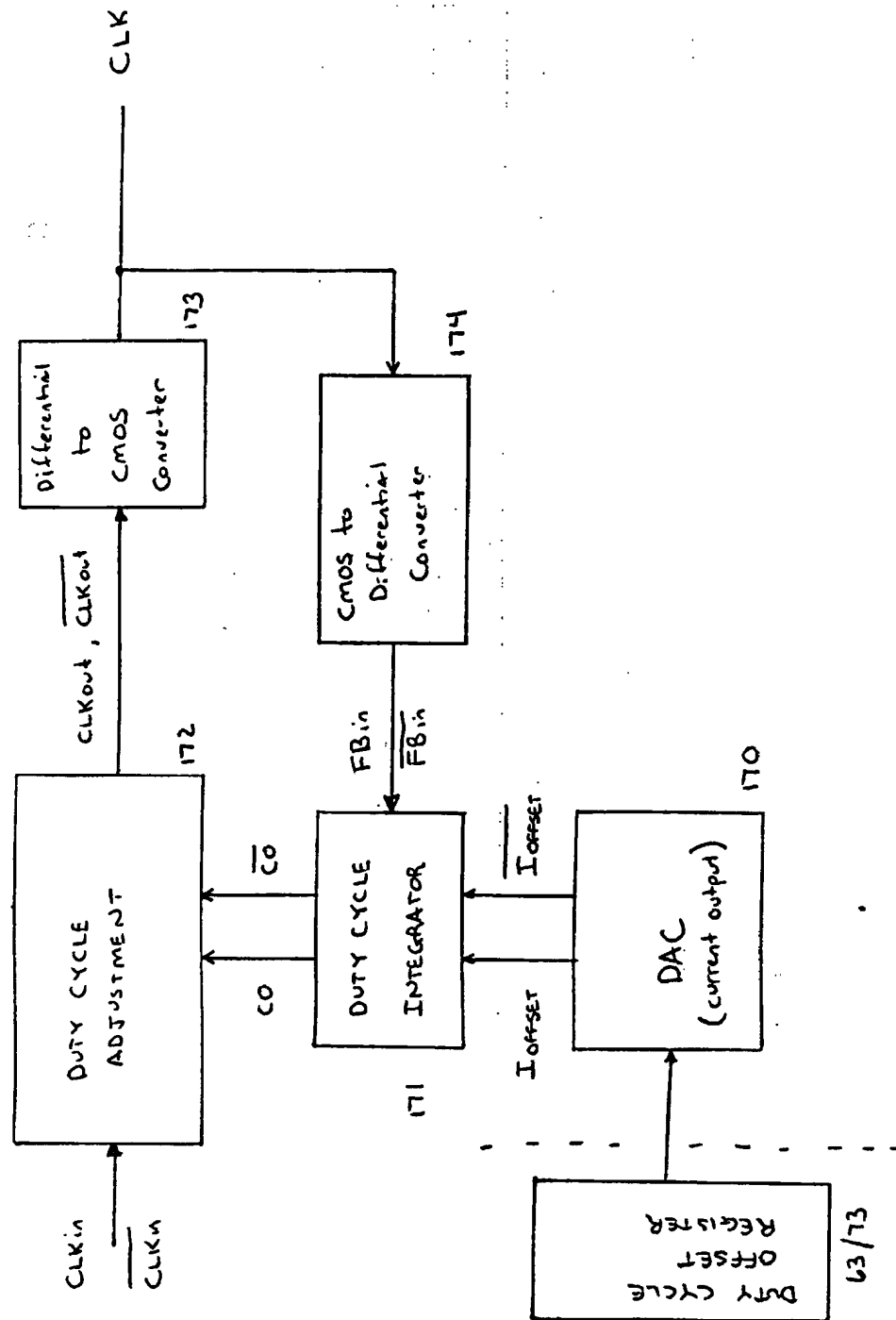


Figure 17

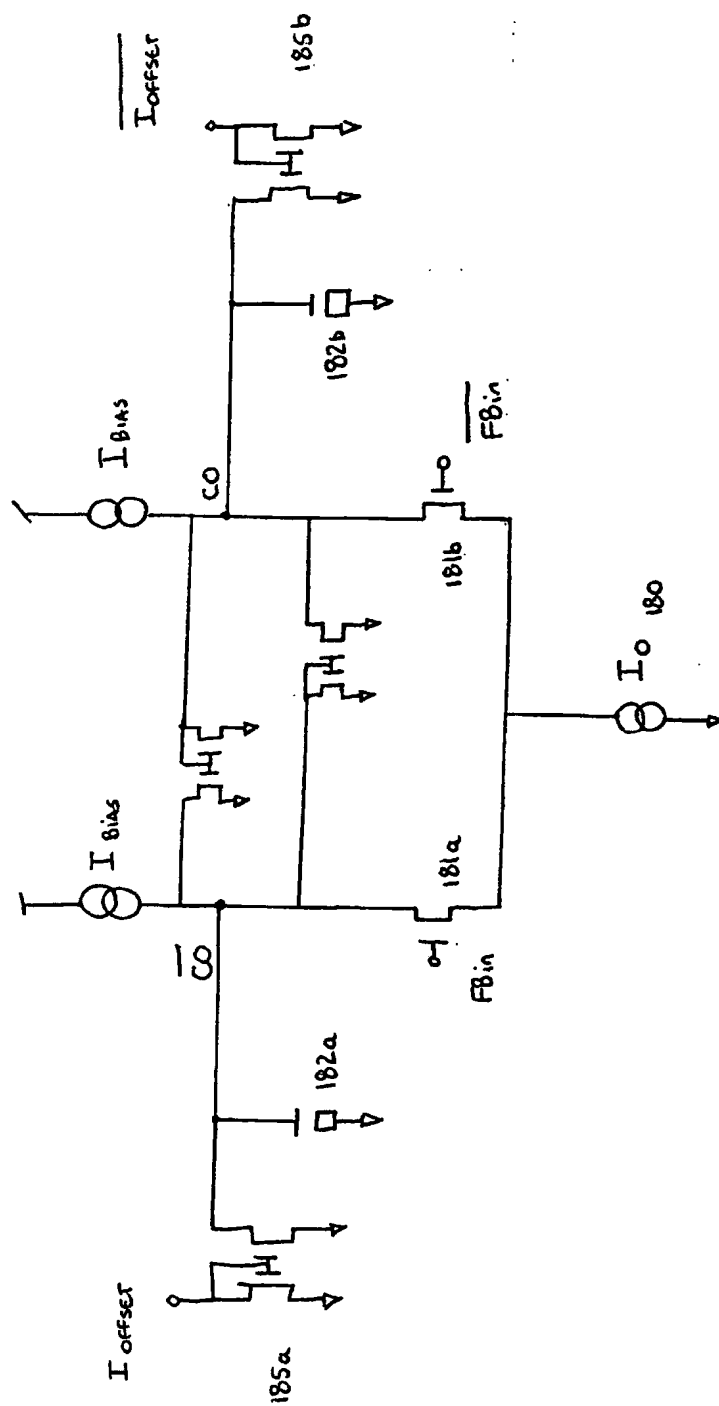


Figure 18

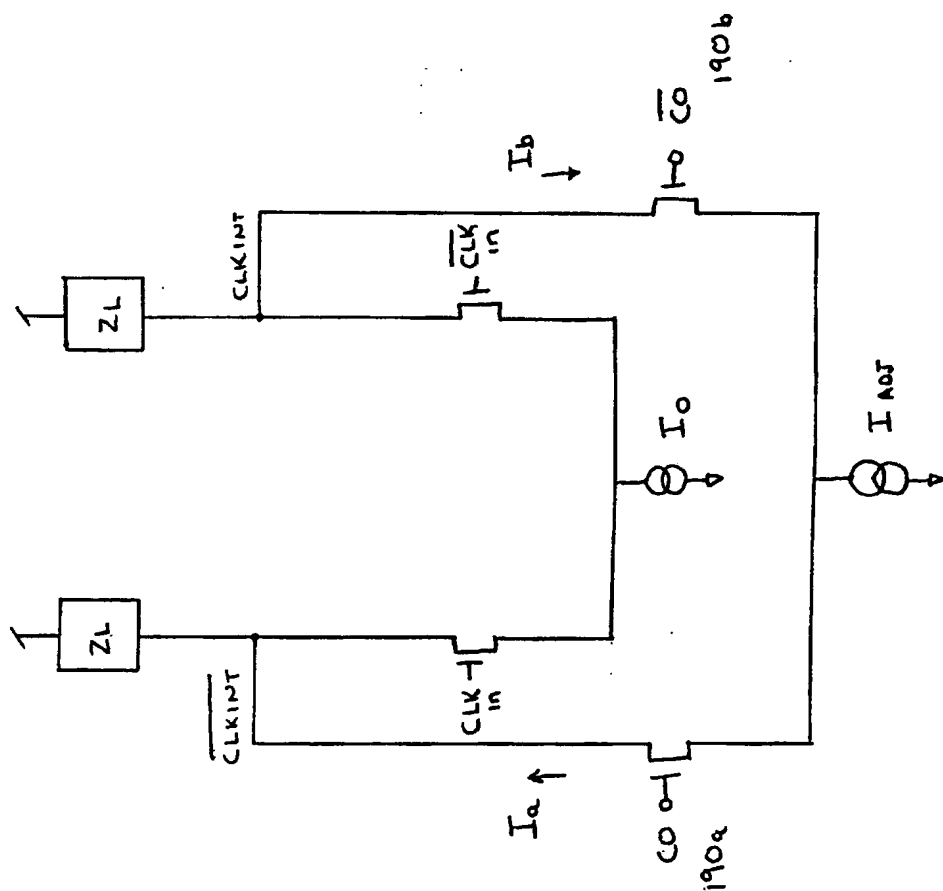
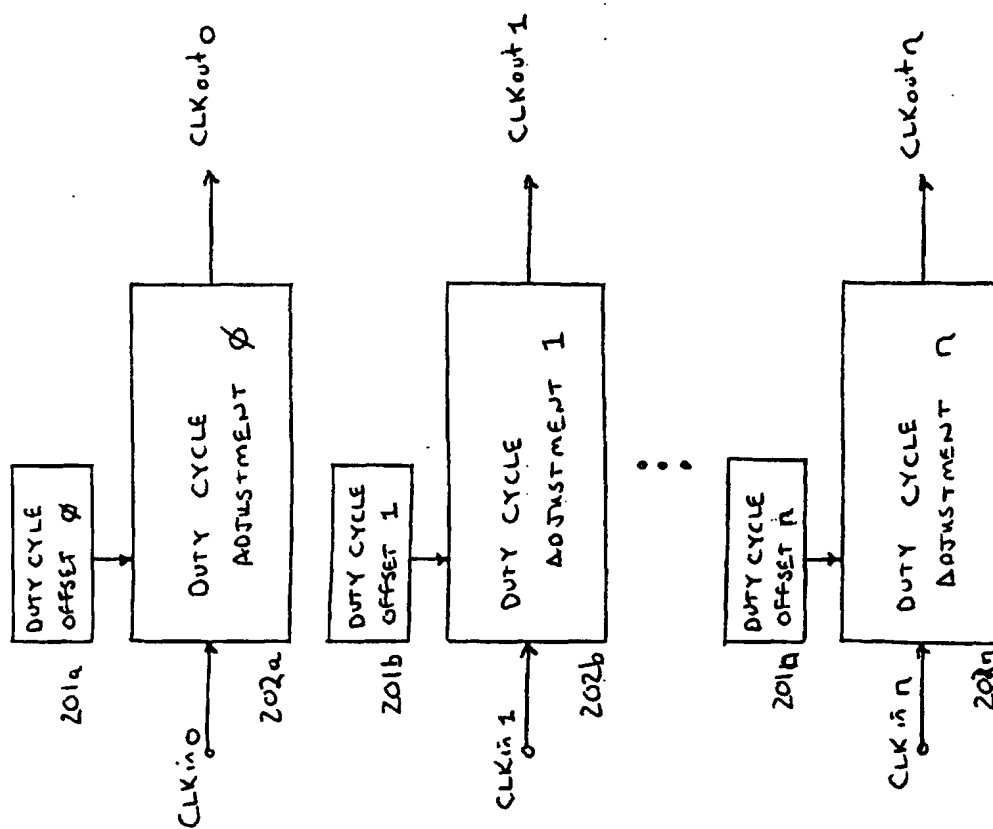


Figure 19

Figure 2 ϕ

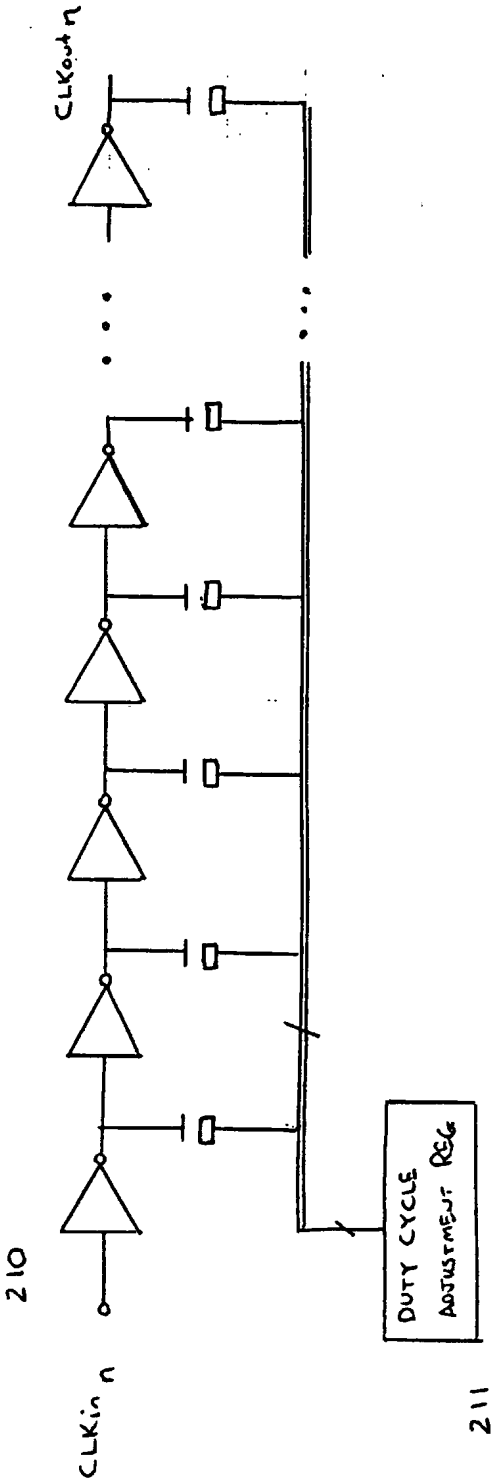


Figure 21

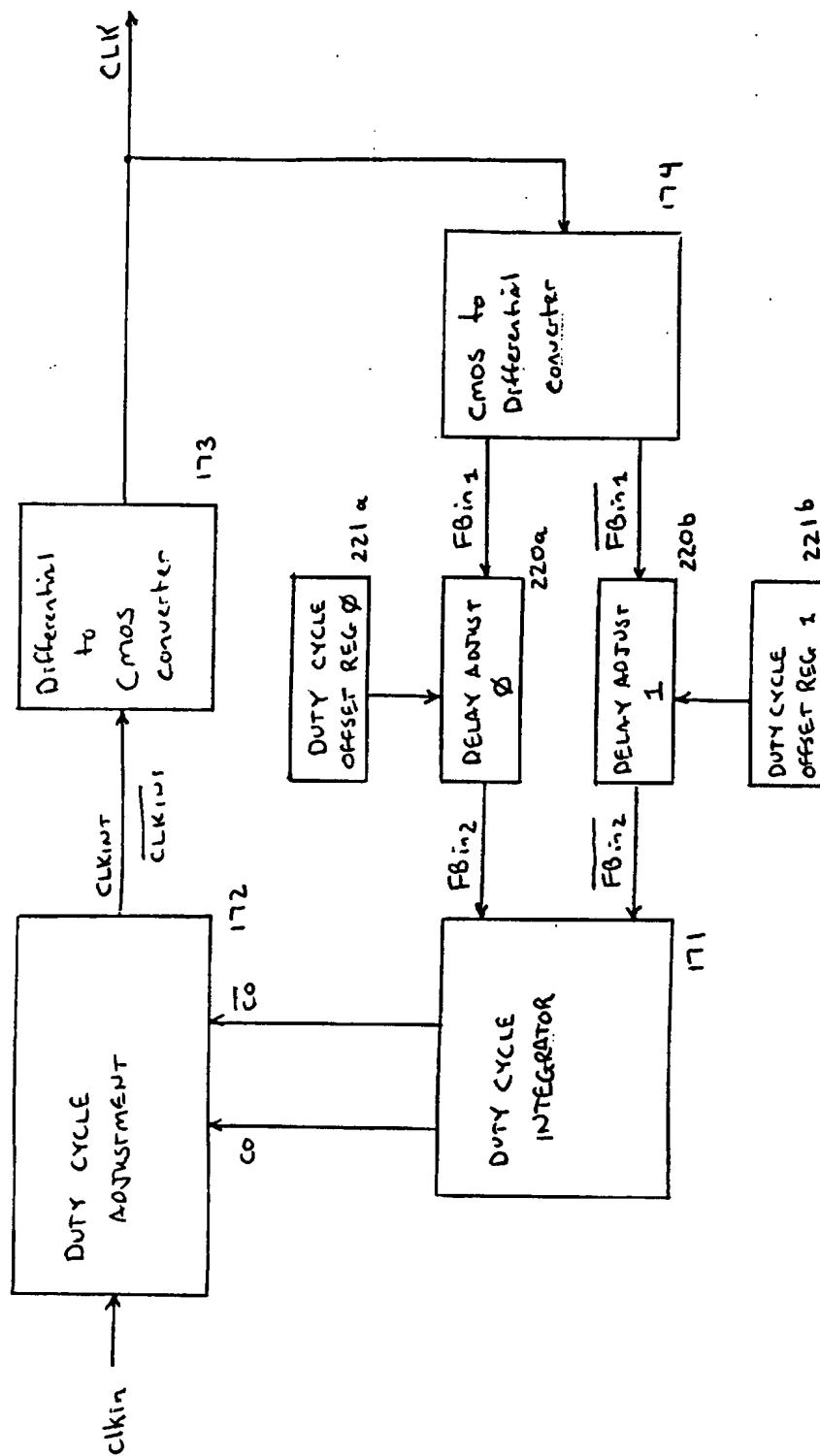


Figure 22

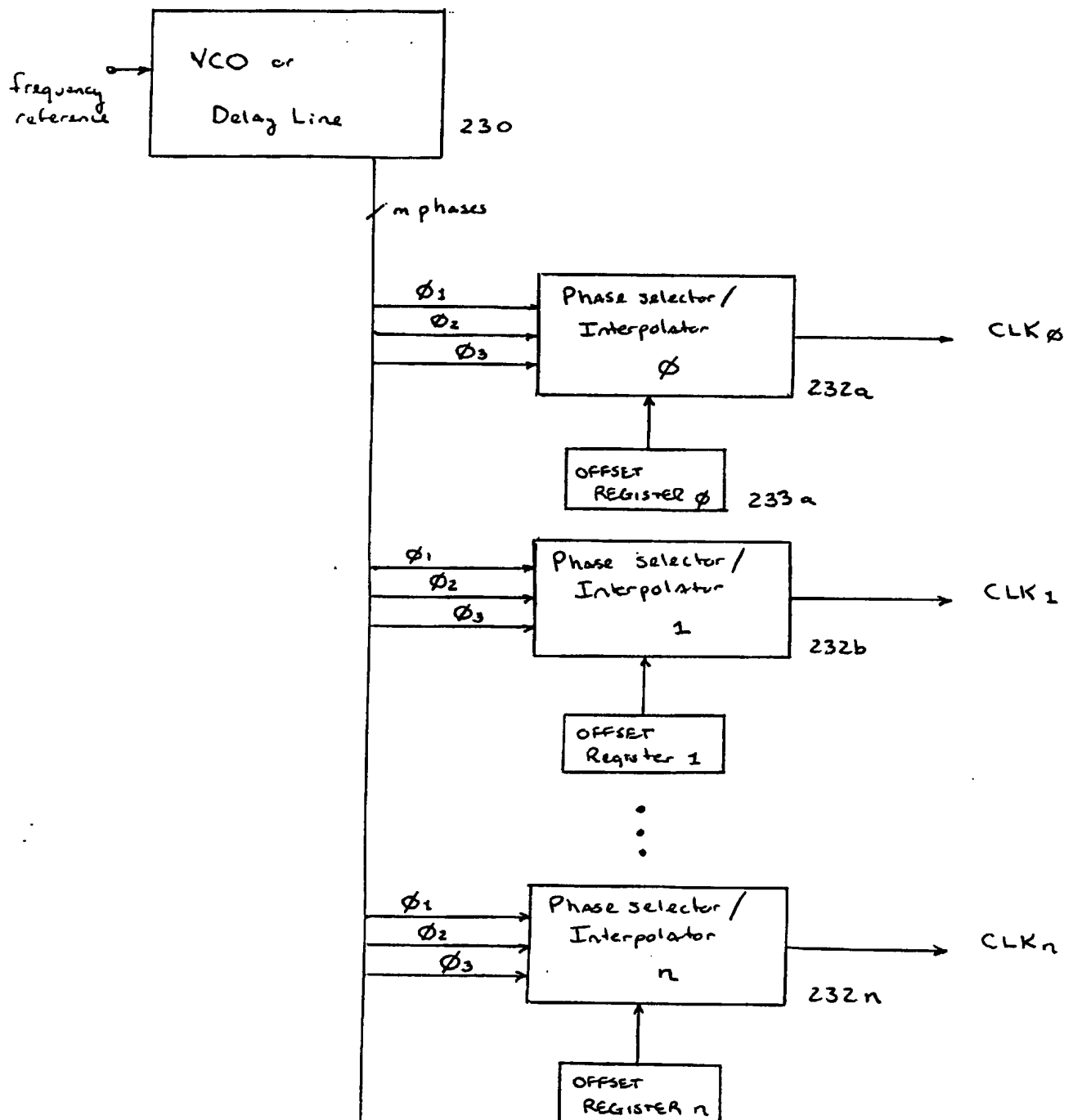


Figure 23

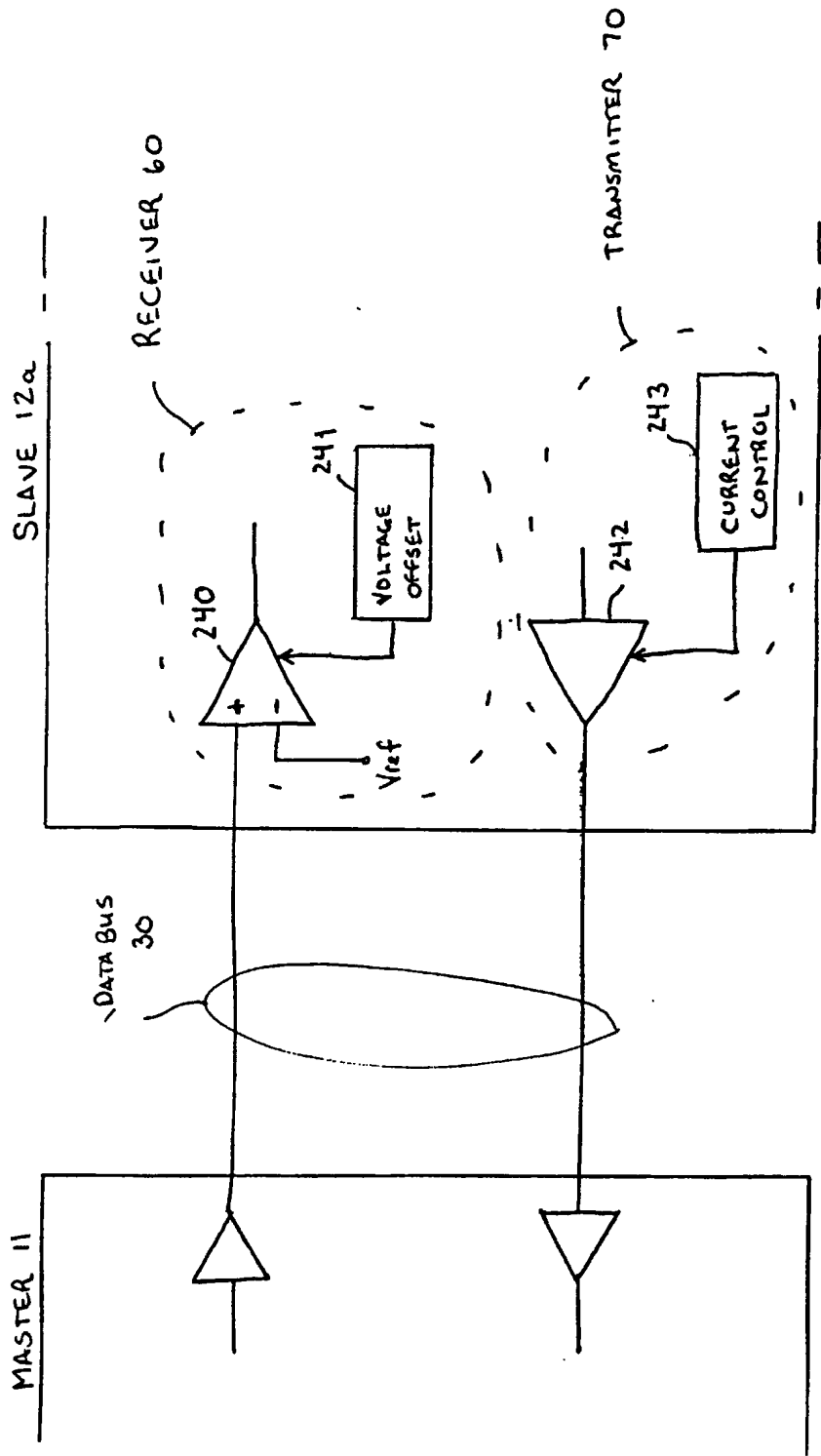


Figure 24

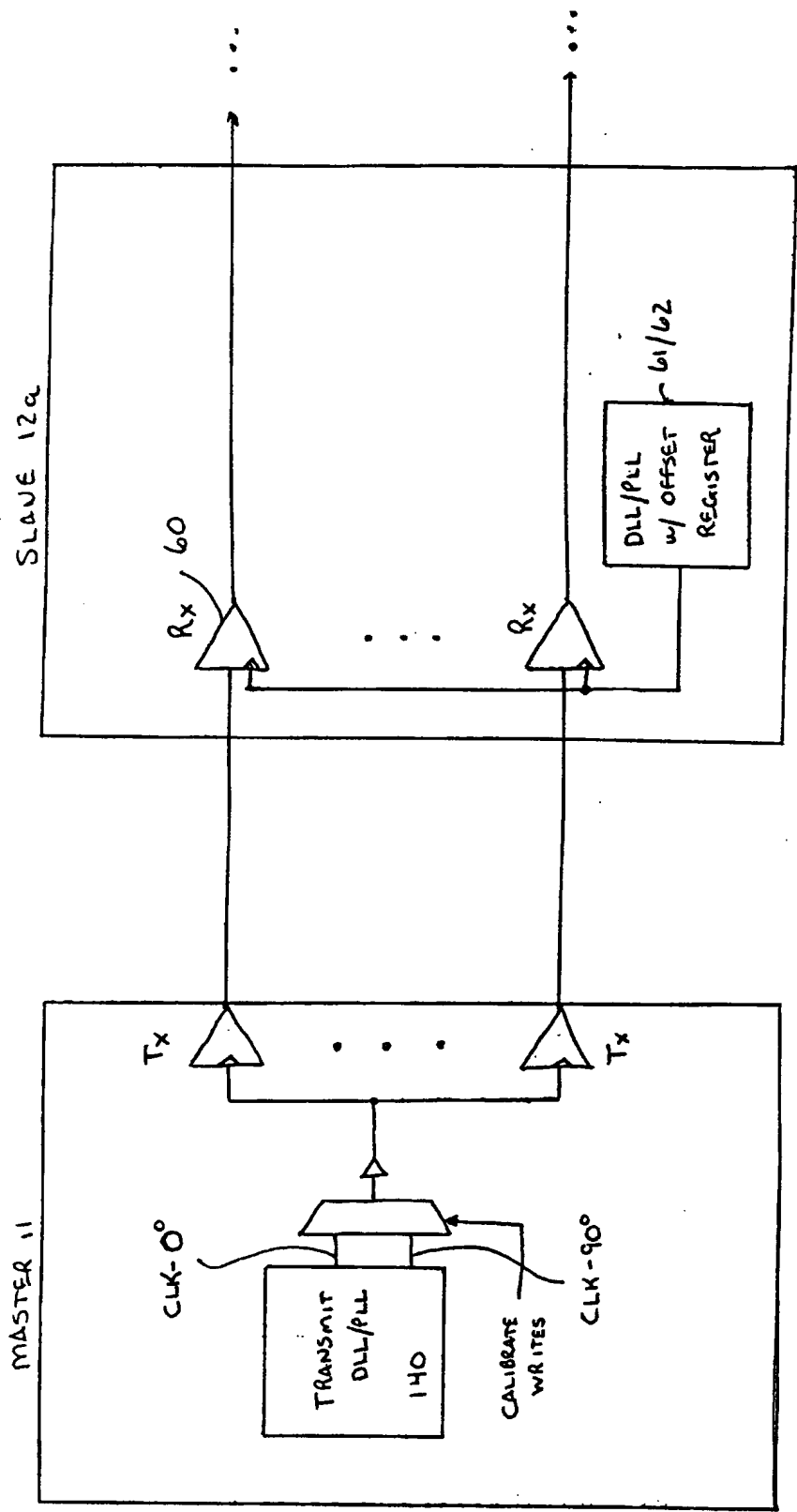


Figure 25

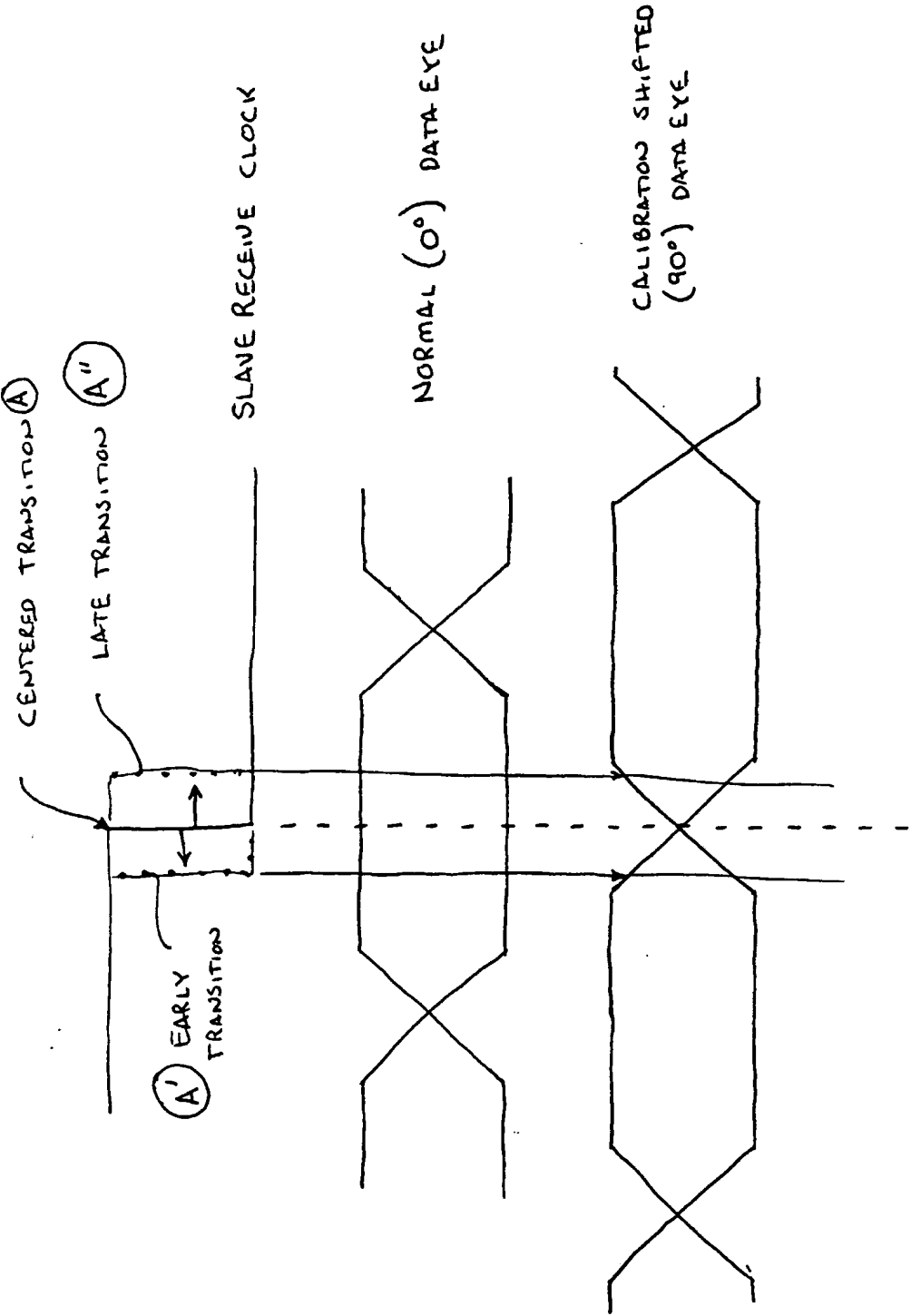


Figure 26

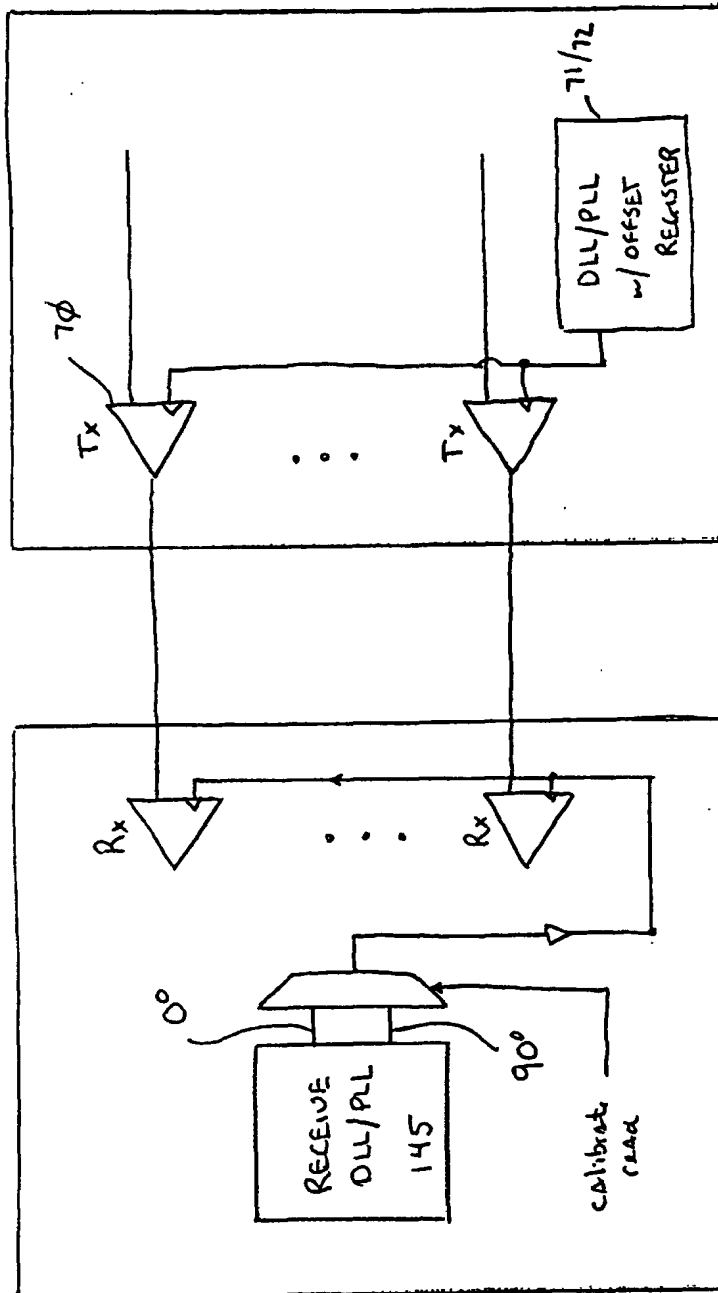


Figure 27

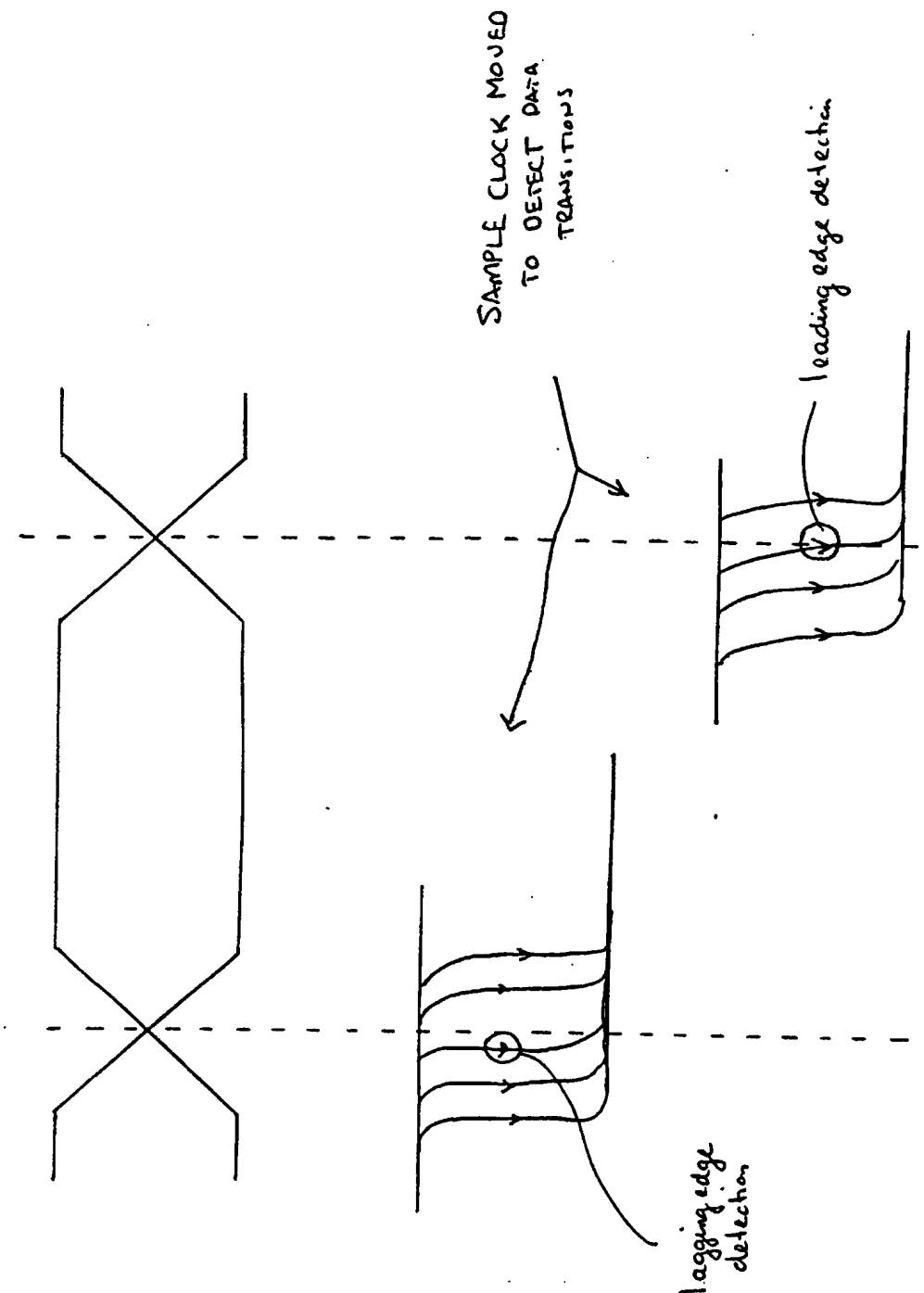


Figure 28

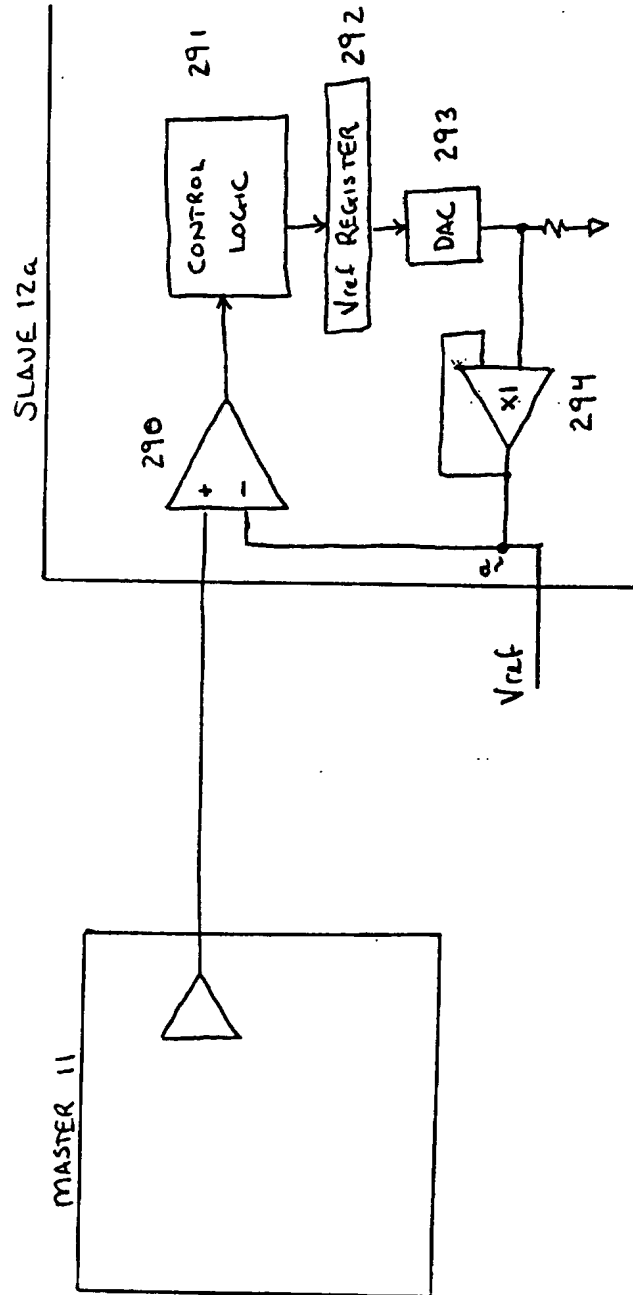


Figure 29

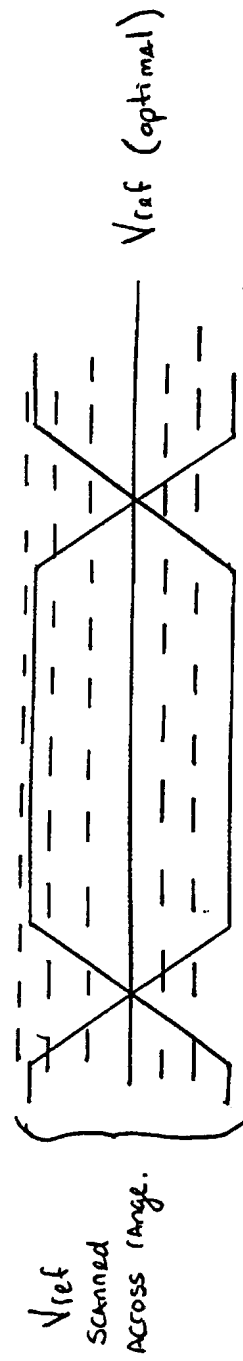


Figure 30

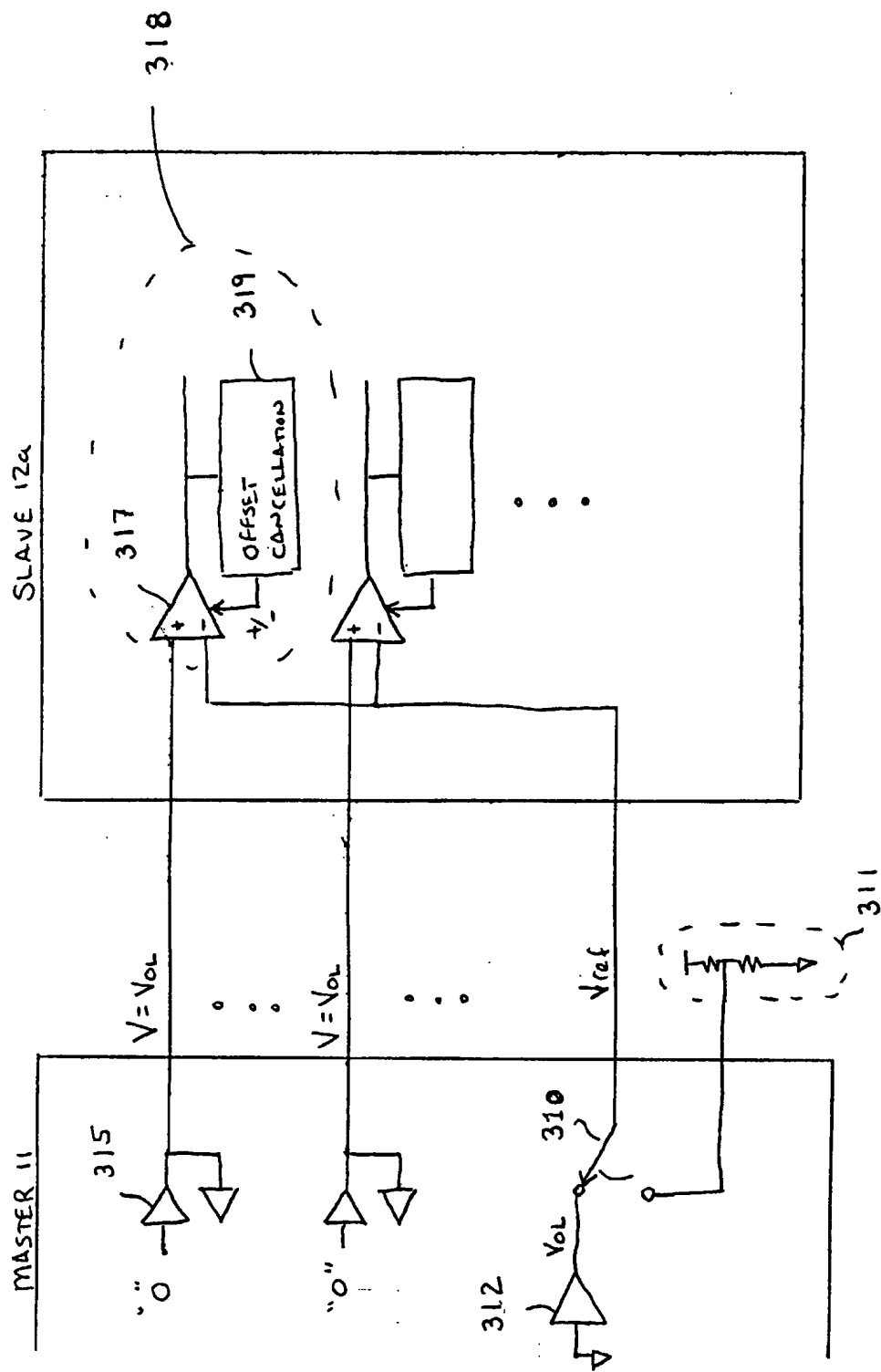


Figure 31

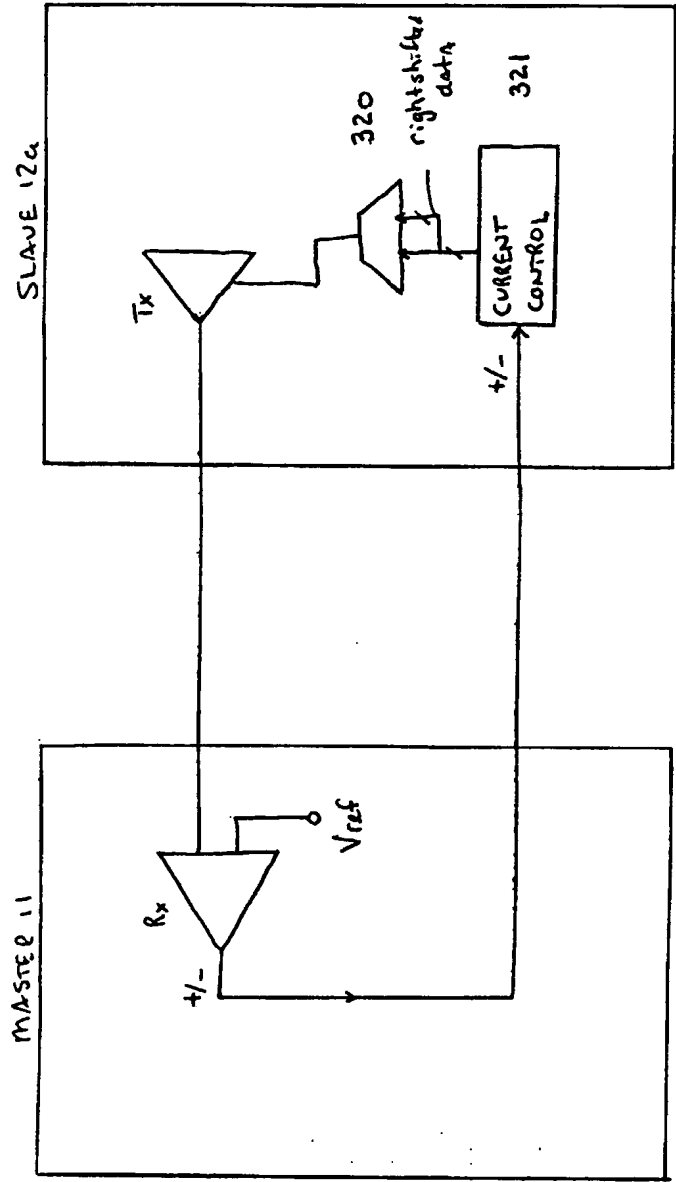


Figure 32

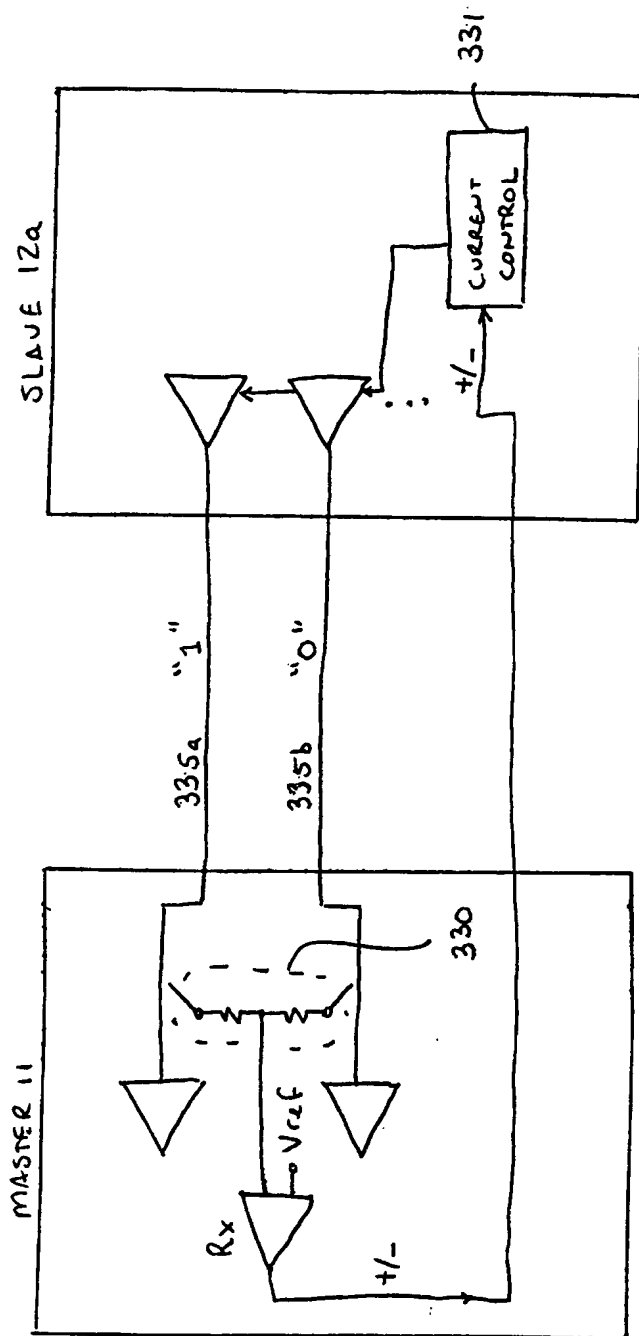


Figure 33

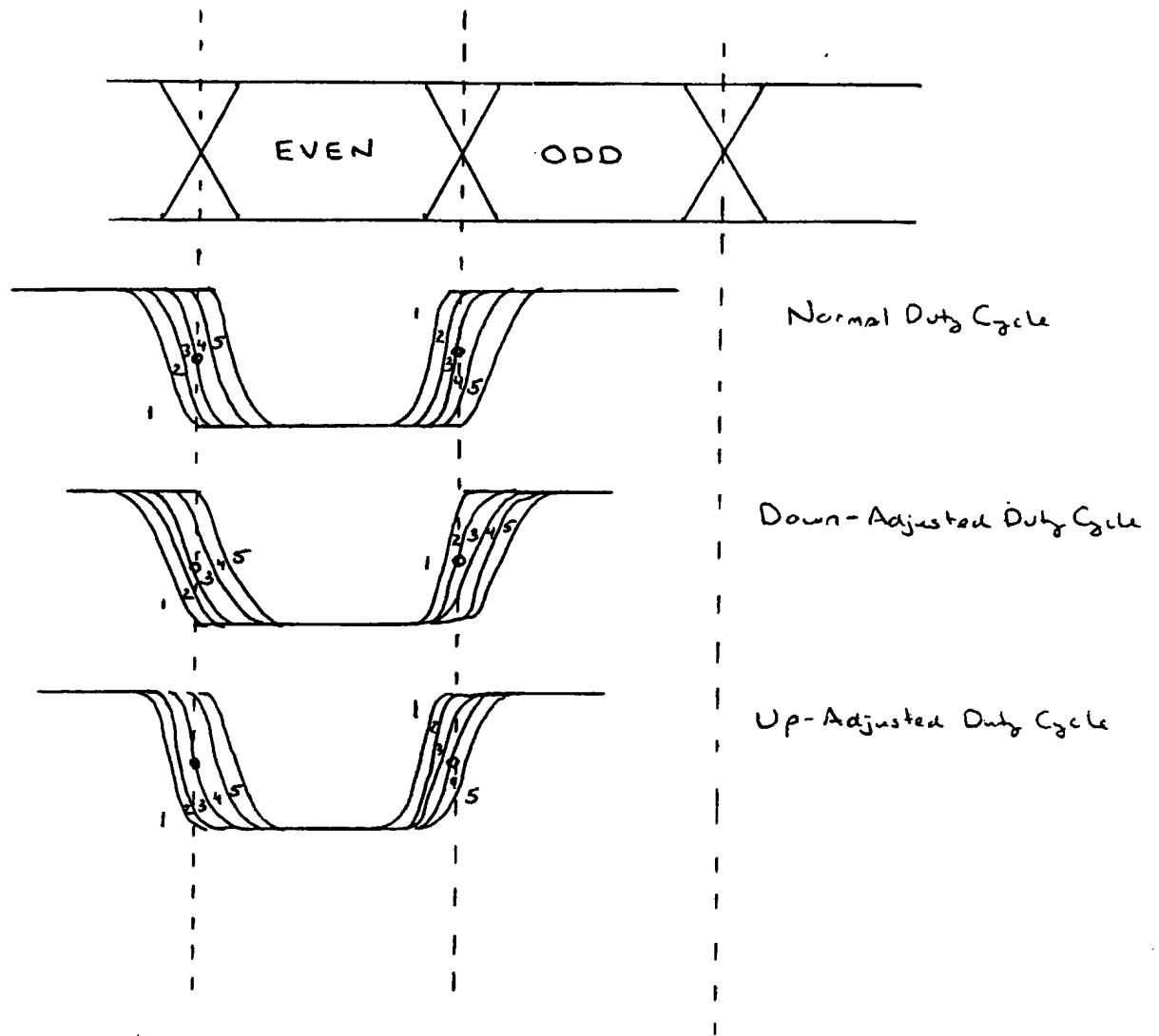


Figure 34

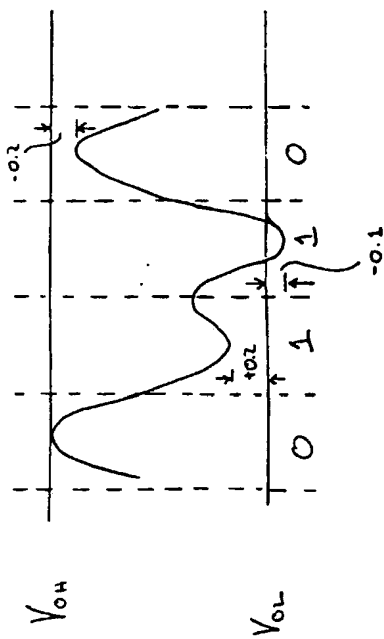


Figure 35

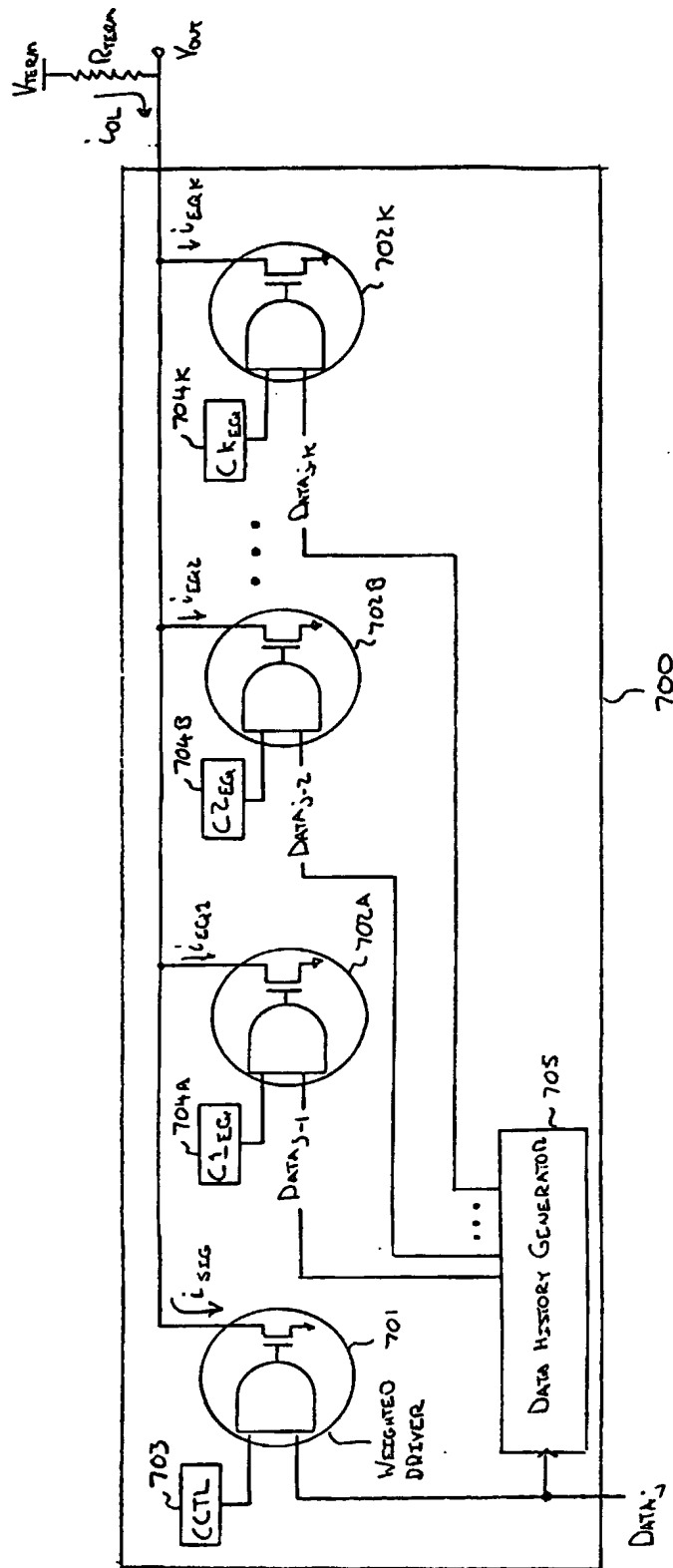


Figure 36A

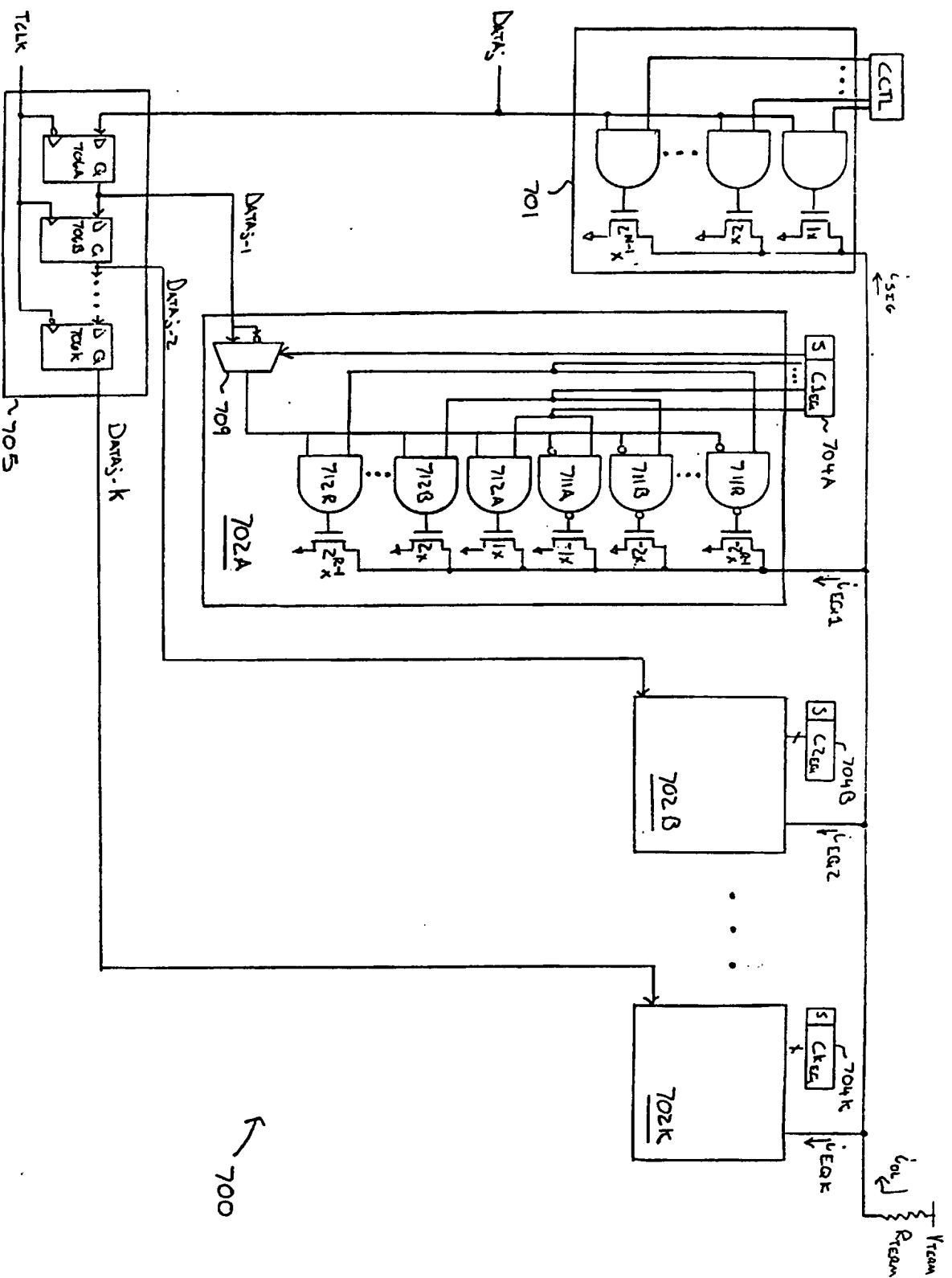


Figura 368

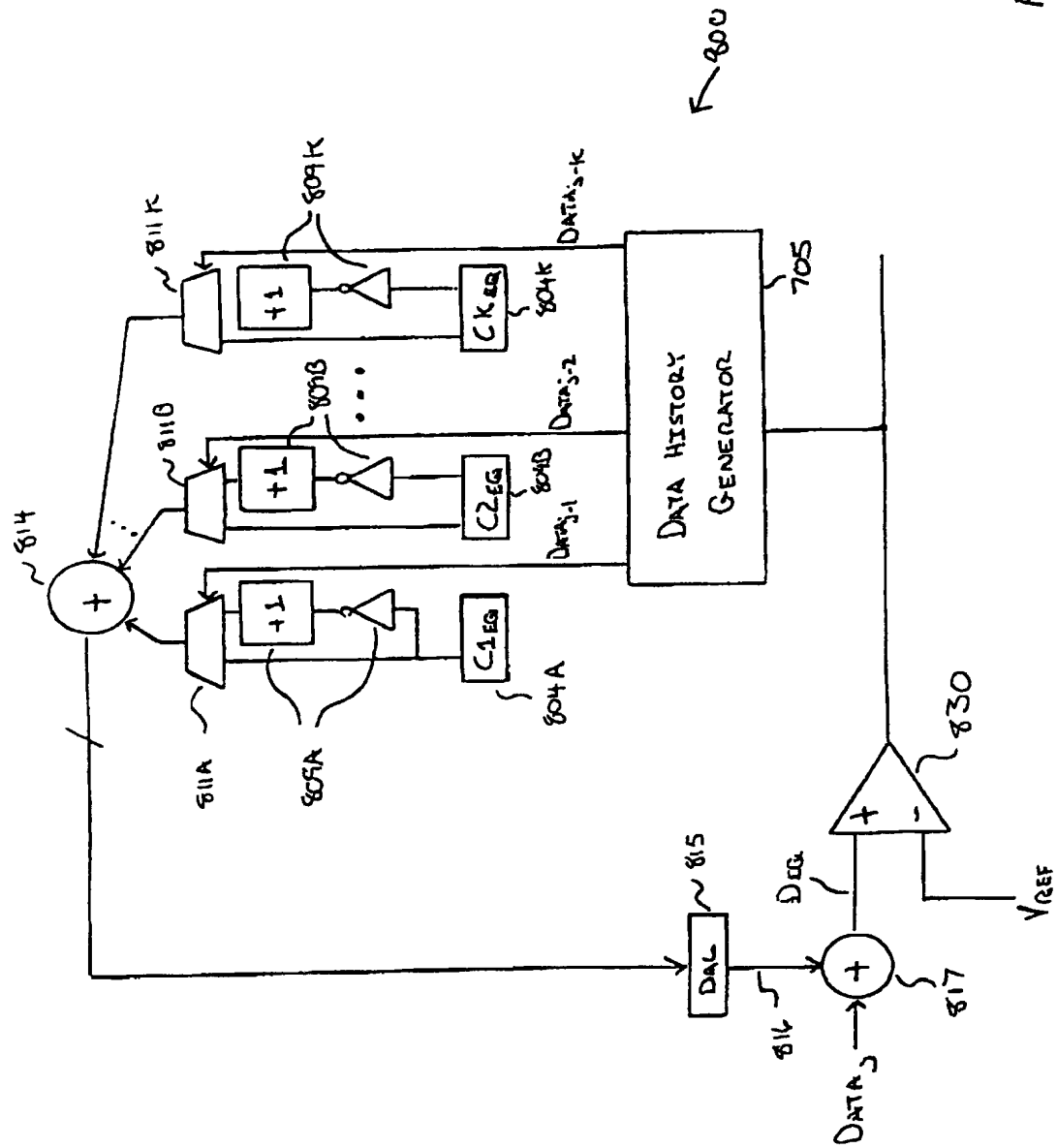


Figure 37

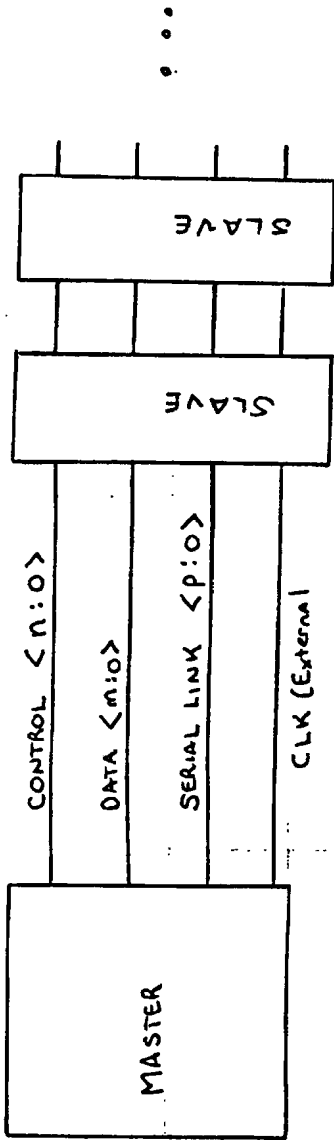


Figure 38

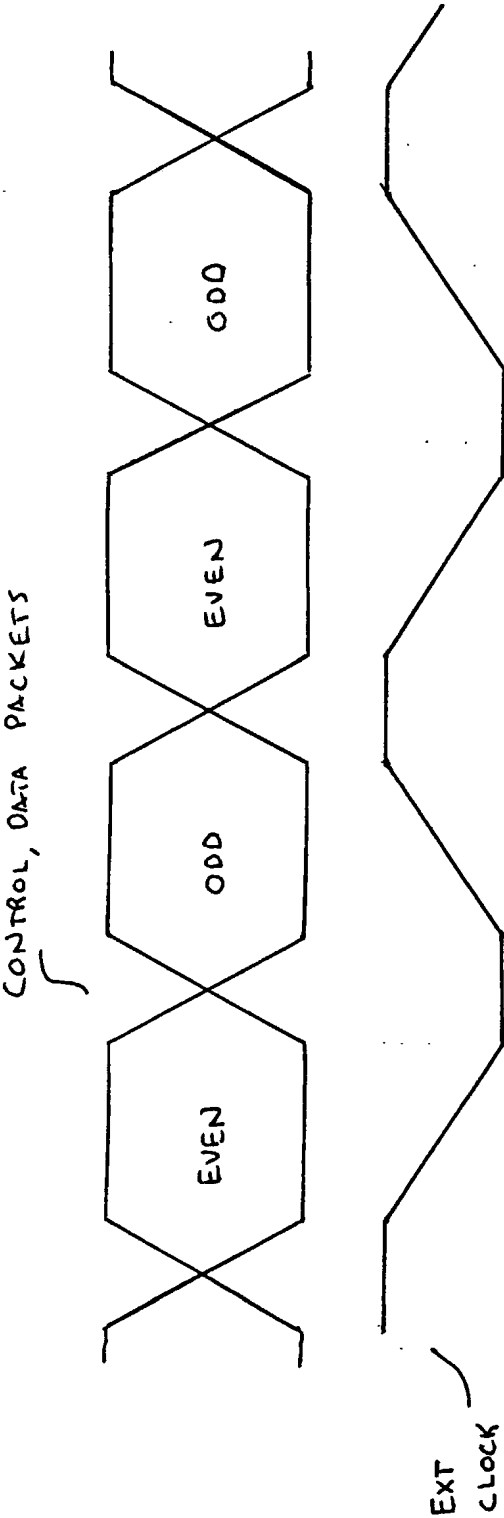


Figure 39

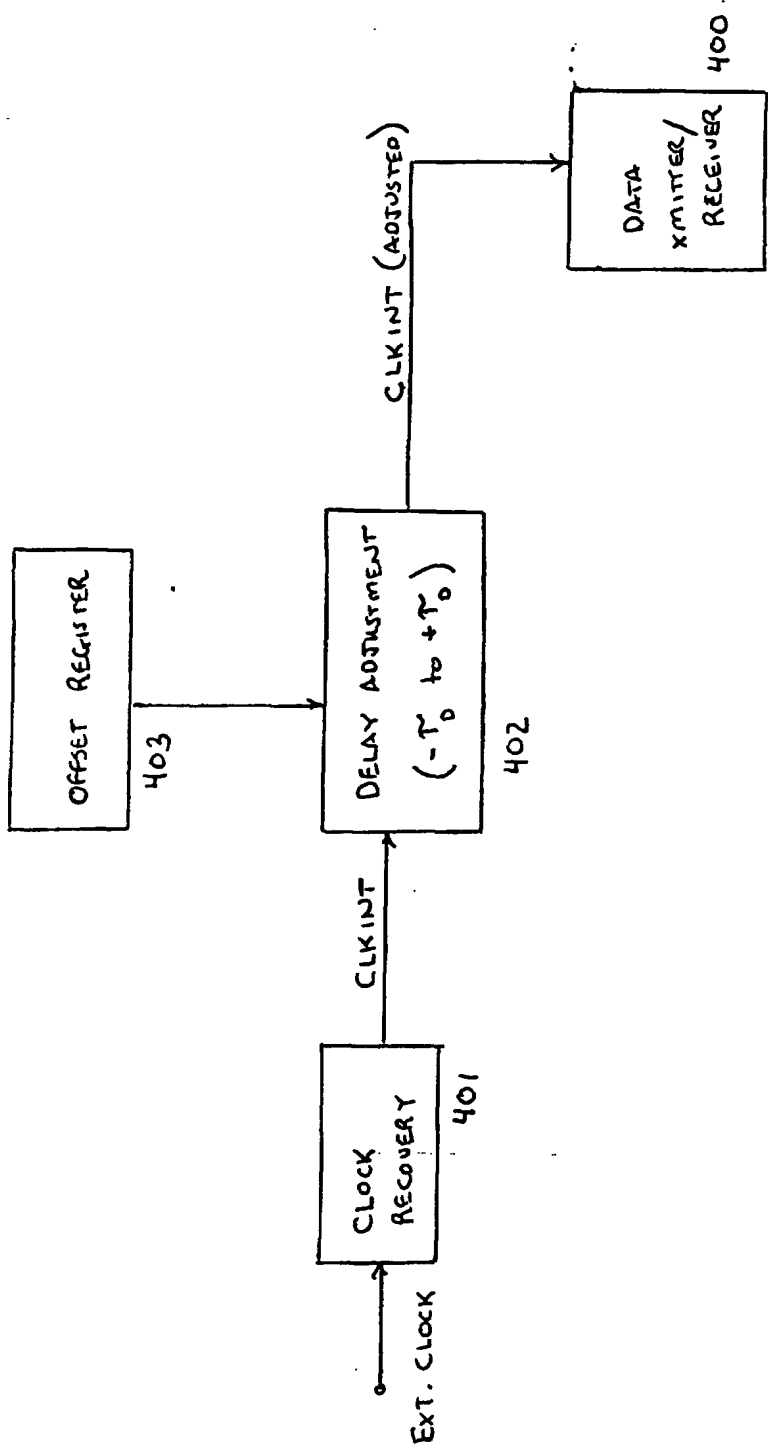


Figure 40

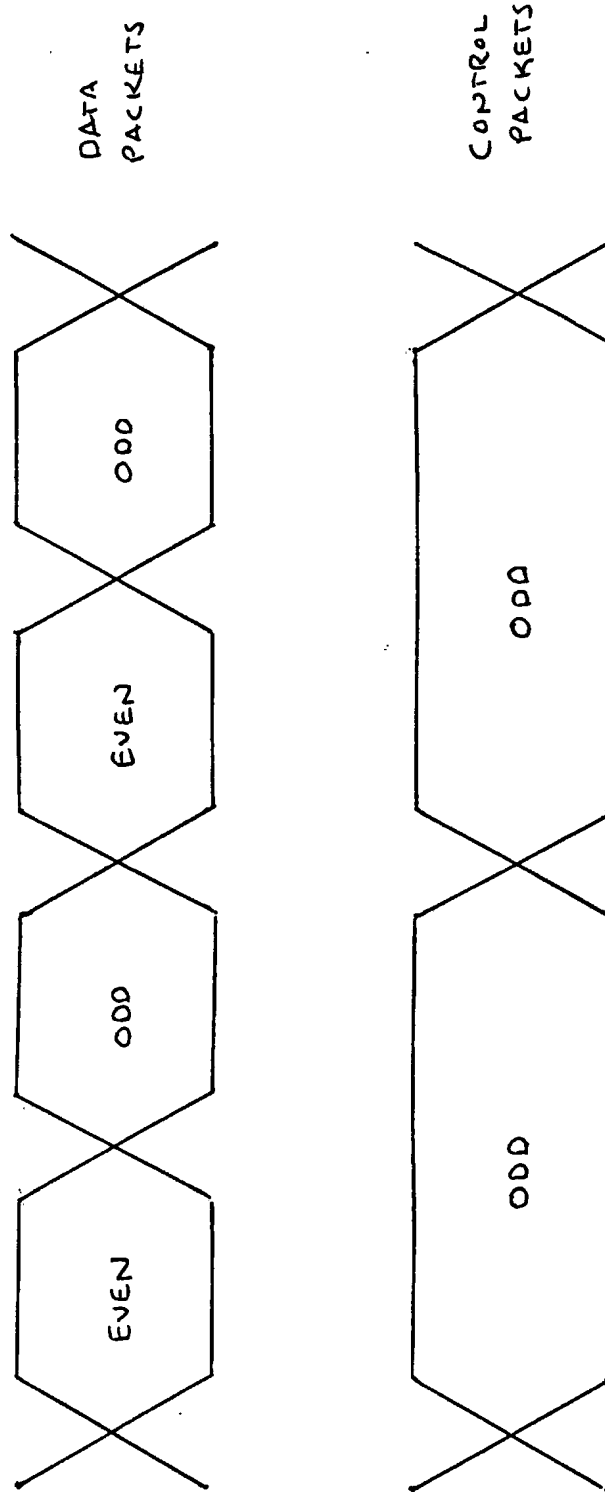


Figure 41

		NORMAL OPERATION FORMAT						CALIBRATION MODE FORMAT					
		c[4]	c[3]	c[2]	c[1]	c[0]	c[4]	c[3]	c[2]	c[1]	c[0]		
EVEN	0	D4	D3	D2	D1	D0	ST	03	02	01	00		
ODD	0	ST	03	02	01	00	ST	03	02	01	00		
EVEN	1	M15	M14	M13	M12	M11	A13	A12	A11	A10	A9		
ODD	1	A13	A12	A11	A10	A9	A3	A12	A11	A10	A9		
EVEN	2	M10	M9	M8	M7	M6	A8	A7	A6	A5	A4		
ODD	2	A8	A7	A6	A5	A4	A8	A7	A6	A5	A4		
EVEN	3	M5	M4	M3	M2	M1	X	A3	A2	A1	A0		
ODD	3	M0	A3	A2	A1	A0	X	A3	A2	A1	A0		

Figure 42

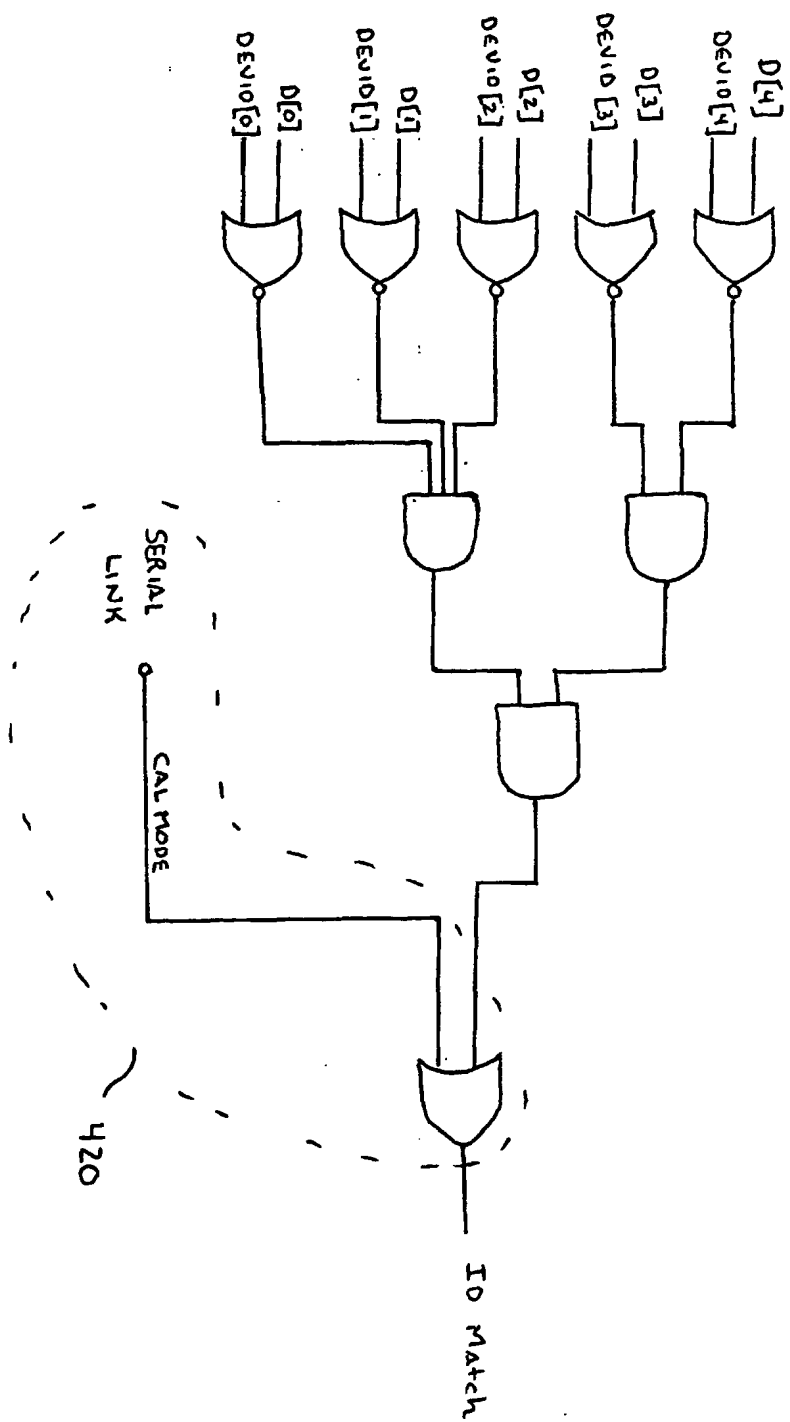


Figure 43

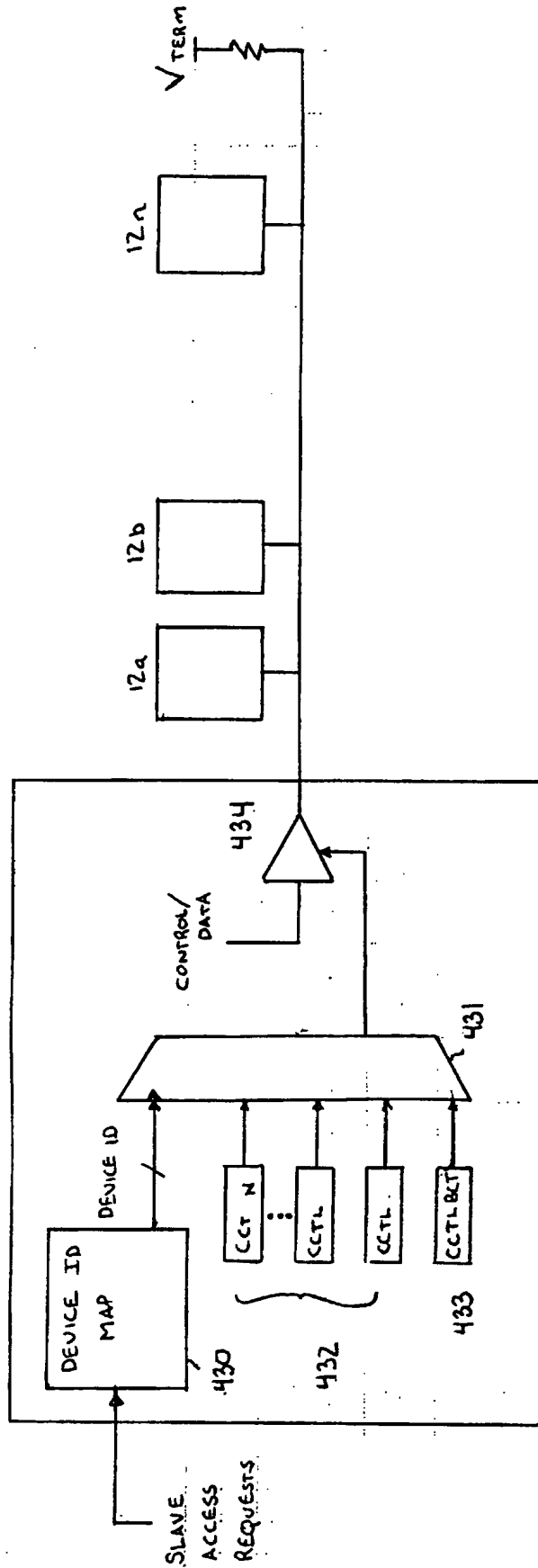


Figure 44

INTERNATIONAL SEARCH REPORT

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A. CLASSIFICATION OF SUBJECT MATTER

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US CL : 710/105

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B. FIELDS SEARCHED

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U.S. : 710/105, 107, 110, 106, 127, 25, 58-61

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NONEElectronic data base consulted during the international search (name of data base and, where practicable, search terms used)
WEST, EAST**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X,P	US 6,085,284 A (FARMWALD et al) 04 July 2000, abstract, col. 4, lines 14-27, col. 18, lines 34-53, col. 19, lines 13-30, col.	1, 8, 17, 18, 22, 24, 34-38, 40, 41, 49, 52, 57, 62, 65-67, 69NO

☐ Further documents are listed in the continuation of Box C.
 ☐ See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be of particular relevance	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E" earlier document published on or after the international filing date	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
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"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

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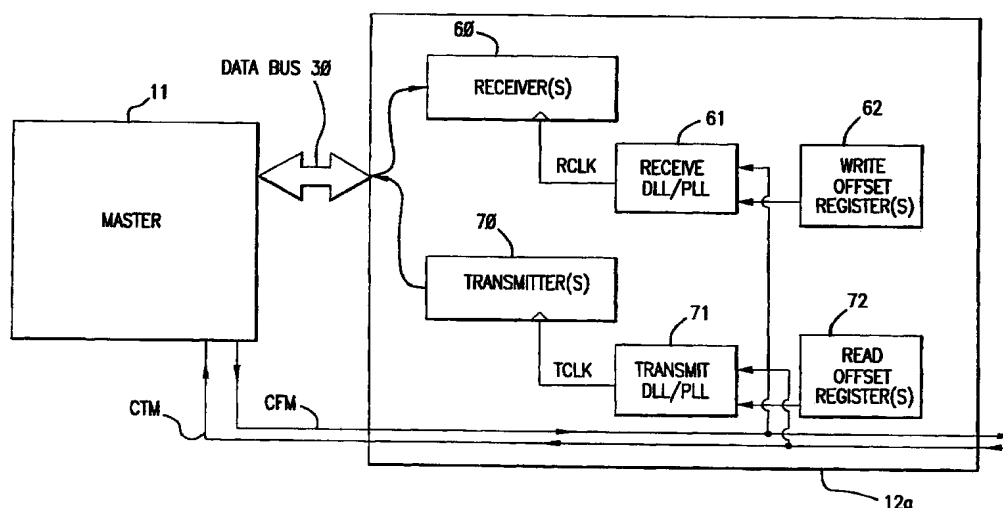
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[Continued on next page]

(54) Title: BUS SYSTEM OPTIMIZATION



(57) Abstract: A bus system comprising a master (11) connected to one or more slave devices (12a-n) via a bus (30) is disclosed. The bus system is able to effectively communicate control information during a calibration phase and to individually determine appropriate timing and/or voltage offsets for each slave device (12). The offsets are used to optimize transfer timing (including duty cycle characteristics), signal equalization, and voltage levels for data exchanged between the master (11) and the slave devices (12a-n).

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BUS SYSTEM OPTIMIZATION

FIELD OF THE INVENTION

The present invention relates to bus systems. More particularly, the present invention relates to a method and apparatus for optimizing the voltage and timing characteristics in a bus system, and to a method for transmitting control information during system calibration.

BACKGROUND OF THE INVENTION

Computer systems and other electrical systems typically use one or more buses to interconnect integrated circuits and other system components. Data, typically in digital form, is communicated between such circuits and components via a bus.

Recent trends in bus development have dramatically reduced the voltage swings associated with different data states on the bus. Early bus systems saw rail-to-rail voltage swings from 3.5 or 5.0 volts down to zero volts. More contemporary bus systems provide voltage swings of less than 1 volt. Limited voltage swings have resulted in reduced power dissipation and lower levels of induced noise on the bus. These reductions are particularly important in the context of bus systems running at ever increasing clock rates.

However, reduced voltage swings and increasing data rates pose considerable problems to the system designer. Reduced voltage swings necessarily provide reduced voltage margins. That is, the ability of system components to distinguish one data state from another on the bus is reduced as the upper and lower swing thresholds move closer together. Similarly, increasing operating frequencies require system components to detect data on the bus during shorter and shorter time intervals. Accordingly, voltage and timing margins for bus signals are often limiting factors in determining overall system performance.

Figure 1 is a simple block diagram of a bus system comprising a master 11 and slaves 12a-12n connected via a data bus 30 and a folded clock signal (Clock-To-Master "CTM" and Clock-From-Master "CFM"). As shown in the related signal timing diagram of Figure 2, valid data is apparent on the data bus during a period T. Ideally, the data signal would be clearly defined at VHI for a first data state and at VLO for a second data state. VHI and VLO would be equally spaced above and below a reference voltage, Vref. Such ideal relationships would provide maximum voltage margin between high and low data states, and

correspondingly optimal signal detection capabilities for system components.

Additionally, data would be detected at time t_1 during the "data eye," i.e., the period ("tbit") during which valid data is on the bus between data transition periods. Time t_1 corresponds to center of the data eye and provides maximum timing margin ($\frac{1}{2}$ tbit) for data
5 detection between data transition periods.

Unfortunately, the ideal voltage and timing margins illustrated in Figure 2 do not exist in actual bus systems. Figures 3A and 3B illustrate typical timing skews between the ideal occurrence of a clock signal within the data eye and actual occurrences. Such clock timing skews arise from many possible sources, such as differences in the manufacture of signal line traces on printed circuit boards, or differences in signal flight time due to the buildup of
10 standing waves induced by signal and clock reflections and noise on signal lines.

In Figure 3A, a CTM signal transition occurs early in the data eye by a period δ before the ideal placement of the CTM transition. In other words, the master reads data from a slave too early relative to the clock by a time δ . In Figure 3B, the CFM signal occurs late in the
15 data eye by the same time. Thus, the master writes data into the slave too late in the data eye by time δ .

Slight differences in the actual timing of the clock signal and/or the data signal will result in a shift of their ideal timing relationship. In addition, the bidirectional nature of some signal lines in the bus system will result in timing shifts of different polarities depending on
20 the direction of data flow.

Each one of the multiple slaves connected to the bus might have a different and unpredictable timing error in relation to the ideal clock placement. Such errors reduce the overall timing margin in the system. Further, as actual transition times wander the hazard arises that a device will attempt to read data during a data transition period, i.e., during a
25 period where the data is not valid on the bus. This hazard increases with system operating frequency.

A comparison between Figures 4A and 4B illustrates the problem of voltage errors in the bus system of Figure 1. In Figure 4A, ideal relationships between VHI, VLO, and Vref are shown, where the voltage swing from VHI to Vref is the same as the voltage swing from Vref to VLO. In one embodiment, VHI is 1.8 volts, Vref is 1.4 volts, and VLO is 1.0 volts.
30 In contrast, the voltage swing from VHI to Vref in Figure 4B is much less than the voltage

swing from Vref to VLO. Such an unequal relationship dramatically reduces the voltage margin for accurately detecting a data value on the bus associated with VHI.

Where the bus system of Figure 1 uses single-ended data and a single reference voltage, as explained below in greater detail, the presence of voltage errors is particularly harmful. For such systems, a reference voltage (Vref) centered between VHI and VLO, such as shown in Figure 4A, would provide maximum voltage margin.

Unfortunately, a number of system phenomenon prevent the stable, centered positioning of VHI and VLO about Vref. For example, channel-DC resistance induces voltages errors in current mode signaling systems. With channel-DC resistance a write data eye can shift in voltage as it goes down the signaling channel. That is, slaves further away from the master are likely to experience smaller voltage swings than the swings of slaves closer to the master, simply due to increasing channel-DC resistance which forms a voltage divider with the termination resistance. In addition, setting output voltage levels to be symmetric about Vref in manufactured systems which experience real process, voltage, and temperature variations is very difficult.

At some point, like the timing errors illustrated above, voltage errors will result in a data error. At a minimum, the presence of voltage errors will reduce the voltage margins allowed within a bus system.

Recognizing the inevitable degradation of the timing and voltage characteristics of bus system signals and the problems associated with same, conventional bus systems sought to compensate for the timing and voltage errors by gross adjustments of the data and/or clock signals in the master. This approach improved signaling margins where degradations were predictable, or where a very limited number of components were connected to a simple bus. However, as bus systems have increased in complexity and size, it has become clear that many factors adversely impacting timing and voltage margins are unique to individual slave devices, or to the relative position of the slave to the master within the overall system.

Thus, the conventional use of timing and voltage offsets in the master has proved ineffective. Similarly, the use of vernier re-calibration techniques has resulted in inconsistent system performance and unacceptable bandwidth degradation in high frequency systems. Accordingly, a need remains for an approach to timing and voltage error compensation which is reliable and well adapted to complex, high frequency bus systems.

SUMMARY OF THE INVENTION

The present invention provides a method and apparatus for effectively adjusting the timing and/or the voltage characteristics of data signals sent via a bus between a master and one or more slave devices. The present invention is particularly well adapted for use in bus systems having a plurality of slave devices since the timing and voltage adjustment may be performed on a slave device by slave device basis. By compensating for voltage and timing skews on an individual basis, the data transfer via the bus may be optimized.

In one general aspect of the present invention, offset values associated with each slave device are used to adjust timing and/or voltage characteristics. Timing and associated offset values may be generally referred to "write" and "read." These terms are used simply to distinguish the direction of data transfer between the master and slave and are not used as limited to classic memory device WRITE and READ operations.

The offset values described in the present invention are typically used in conjunction with a clocking circuit, such as a delay locked loop or phase locked loop, to generate read/write clock signals internal to each slave device.

In another aspect of the present invention, a timing adjustment circuit is provided in each slave device to generate an optimized internal read/write clock signal. This internal read/write clock signal is typically derived in relation to a master clock signal applied to the slave device and an offset value.

The timing adjustment circuit may take many forms and may make timing adjustments in absolute time, as well as in degrees. In several of these forms a read/write offset feedback signal is developed in relation to the offset value(s) and used to generate the internal read/write clocking signal.

In a second general aspect, the present invention uses offset values specifically determined with respect to each slave device to adjust the voltage level(s) of data received by the slave device and/or the voltage level or drive current for data being transmitted by the slave device.

The present invention is also directed to an apparatus and method for determining the relevant timing and/or voltage offsets for each slave device in the bus system. The determination of these offsets is often made during a calibration phase of operation for the bus system. During calibration, the bus system may communicate control information using

a protocol or control information packet which differs from the protocol or control information packet used during normal bus system operation.

5 In yet another aspect of the present invention, one or more offset values, either voltage or timing, are stored in one or more registers on the master. A mean or common offset value may be stored in the master and applied to each slave device, or individual offset values corresponding to each slave may be stored in the master and selected, as appropriate, when data is sent to or received from the slave. Thus, the present invention contemplates slave resident adjustment circuits and master resident adjustment circuits for both timing and voltage aspects.

10 In similar vein, duty cycle adjustment may be made within a bus system according to the present invention. Further, signal equalization may also be adjusted using the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a block diagram of a bus system;

Figure 2 is a timing diagram illustrating an ideal relationship between a data eye and a read/write clock signal;

5 Figures 3A and 3B are timing diagrams illustrating typical timing relationships between a data eye and a read/write clock signal;

Figures 4A and 4B are swing voltage diagrams illustrating the difference between an ideal voltage swing and a typical voltage swing;

10 Figure 5 is a block diagram of a bus system showing exemplary channel signaling in some greater detail;

Figure 6 is a block diagram generally illustrating the timing adjustment aspect of the present invention as applied to a typical slave device/master device relationship;

Figure 7 is a circuit diagram showing a first embodiment of a timing offset circuit according to the present invention;

15 Figure 8 is a circuit diagram showing a second embodiment of a timing offset circuit according to the present invention;

Figure 9 is a circuit diagram showing a third embodiment of a timing offset circuit according to the present invention;

20 Figure 10 is a circuit diagram showing a fourth embodiment of a timing offset circuit according to the present invention;

Figure 11 is a circuit diagram showing a fifth embodiment of a timing offset circuit according to the present invention;

Figures 12A and 12B illustrate data transmission timings in an exemplary double-data-rate system;

25 Figure 13 is a block diagram illustrating the addition of a duty cycle offset register(s) to one embodiment of a bus system within the context of the present invention;

Figure 14 is one embodiment of a duty cycle adjustment mechanism adapted for use with the duty cycle registers shown in the system of Figure 13;

30 Figure 15 is a more detailed exemplary circuit showing one possible implementation of the duty cycle adjustment circuit shown in Figure 14;

Figure 16 is a waveform diagram illustrating certain relationships between the signals

apparent in the foregoing duty cycle adjustment circuit;

Figure 17 is another embodiment of a duty cycle adjustment mechanism adapted for use with the duty cycle registers shown in the system of Figure 13;

5 Figure 18 is a more detailed exemplary circuit showing one possible implementation of the duty cycle integrator shown in Figure 17;

Figure 19 is a more detailed exemplary circuit showing one possible implementation of the duty cycle adjustment circuit shown in Figure 17;

Figure 20 is a block diagram illustrating duty cycle adjustment scheme within the context of the present invention as applied to an N-data-rate system;

10 Figure 21 is a more detailed exemplary circuit showing one possible implementation of the duty cycle adjustment circuit(s) shown in Figure 20;

Figure 22 is yet another embodiment of a duty cycle adjustment mechanism adapted for use with the duty cycle register(s);

15 Figure 23 is a block diagram illustrating another duty cycle adjustment scheme within the context of the present invention as applied to an N-data-rate system;

Figure 24 is a block diagram generally illustrating the voltage adjustment aspect of the present invention as applied to a typical slave device/master device relationship;

Figure 25 is a block diagram illustrating a first approach to timing calibration consistent with the present invention;

20 Figure 26 is a timing diagram illustrating the timing calibration approach shown in Figure 25;

Figure 27 is a block diagram illustrating a second approach to timing calibration consistent with the present invention;

25 Figure 28 is a timing diagram illustrating a scanning window approach to timing calibration;

Figure 29 is a block diagram illustrating a scanning window approach to voltage calibration;

Figure 30 is a voltage diagram illustrating the scanning window approach of the circuit in Figure 29;

30 Figure 31 is a block diagram illustrating a first embodiment of a voltage calibration circuit consistent with the present invention;

Figure 32 is a block diagram illustrating a second embodiment of a voltage calibration circuit consistent with the present invention;

Figures 33 is a block diagram illustrating a third embodiment of a voltage calibration circuit consistent with the present invention;

5 Figure 34 is a waveform diagram illustrating an adapted scanning window approach to duty cycle adjustment calibration;

Figure 35 is a waveform diagram illustrating an unequalized data transmission;

Figure 36A and 36 B are exemplary transmitter-side output driver circuits comprising a temporal equalization circuit;

10 Figure 37 is an exemplary receiver-side equalization circuit;

Figure 38 is a block diagram of a bus system highlighting additional channel signals over those shown in Figures 1 and 5;

Figure 39 is a timing diagram illustrating even and odd data packet definitions relative a clock signal;

15 Figure 40 is a block diagram generally illustrating the timing adjustment aspect of the present invention in relation to one exemplary bus system;

Figure 41 is a timing diagram illustrating one exemplary relationship between expanded control packets and normal data packets;

20 Figure 42 illustrates changes in the format of an exemplary control information packet as between normal mode of operation and a calibration mode of operation;

Figure 43 illustrates the changes to a selected exemplary decoding circuit required to implement the different mode of interpretation of the control information packet shown in Figure 26; and,

25 Figure 44 generically illustrates the placement of one or more "offset registers" within the master as compared with the former slave resident registers.

DETAILED DESCRIPTION

In order to better understand the use, implementation, and associated benefits of the present invention, a general bus system readily adapted to the present invention will be described with reference to Figure 5. In the block diagram of Figure 5, a bus system 10, shown in some additional detail with reference to the bus system shown in Figure 1, comprises bus 30 coupled between a master 11 and a plurality of slaves 12a-12n. Bus 30 is a high speed, low voltage swing bus comprising multiple signal lines and transferring data between slaves 12a-12n and master 11.

Master 11 and each slave 12a-12n typically include an interface circuit (not shown) coupling the respective device to bus 30. Within bus system 10, a master can communicate with another master (not shown) and with slaves 12a-12n. In contrast, slaves only communicate with masters.

Master 11 contains intelligence and generates commands to the slaves. Master 11 may be a microprocessor, a digital signal processor, a graphics processor, peripheral controller, an input/output (I/O) controller, a DMA controller, a memory controller, a communications device, or some other type of intelligent controller.

Slaves require only a low level of intelligence. In one preferred embodiment, slaves 12a-12n are DRAMs, but might be one or more other types of memory devices including electrically programmable read only memories (EPROMs), flash EPROMs, random access memories (RAMs), static RAMs (SRAMs), video RAMs (VRAMs), etc. In another embodiment, slaves 12a-12n are bus transceivers.

Master 11 and slaves 12a-12n each includes Data Bus [8:0] pins, at least one BusCtrl pin and BusEnable pin, a ClkToMaster ("CTM") pin, a ClkFrom Master ("CFM"), and a Vref pin. These pins receive and transmit low voltage swing signals and correspond to the channel signal line(s) and buses shown in Figure 5. In the illustrated embodiment, a 9 bit data bus is assumed. However, one of ordinary skill in the art will understand that the data bus might include any reasonable number of signals lines, and is typically part of a larger communication channel having a control bus and/or an address bus.

Master 11 may be configured to communicate control information to slaves 12a-12n in many different ways. The BusCtrl and BusEnable signal paths shown in Figure 1 are typical of such configurations, and may each comprise a single signal line or a number of

signal lines. Further, master 11 and slaves 12a-12n may comprise a daisy chained, initialization signal line connected between the SOut and SIn pins shown in Figure 5.

Data bus signal lines 32 transfer data between master 11 and slaves 12a-12n. The data bus signal lines are transmission lines having controlled impedances. Each data bus signal line 32 is terminated at one end in a termination resistor (collectively shown as 20). The termination resistors are coupled to a termination voltage, V_{term} . The resistance value R of each termination resistor 20 is equal to the line impedance of its data bus signal line 32. Such a configuration helps prevent unwanted signal reflections on the signal line. Other signal lines in memory system 10, such as BusCtrl line 14, BusEnable line 15, CTM line 16a, and CFM line 16b, are similarly terminated, 23, 21, 22, respectively.

Clock line 16 is coupled at one end to a clock 35. In one embodiment, clock 35 is external to and independent of master 11 and slaves 12a-12n. The clock signal generated by clock 35 is carried by clock line 16 to master 11 and slaves 12a-12n. Clock line 16 is folded back to form two line segments 16a and 16b. Segment 16a carries the CTM signal, and segment 16b carries the CFM signal.

Bus system 10 also includes a reference voltage line 17 that couples V_{ref} to each of master 11 and slaves 12a-12n. As shown in Figure 5, voltage V_{ref} is generated in a voltage divider formed by resistors 25 and 26 between termination voltage V_{term} and ground. In addition to V_{ref} , master 11 and slaves 12a-12n are connected to ground (GND) via line 18 and a source voltage V_{DD} via line 19.

In bus system 10, data driven by master 11 propagates past slaves 12a-12n along bus 30. Slaves 12a-12n are able to "sense" the data on the bus in accordance with control information sent from master 11. For example, the master might initiate a transfer of data by broadcasting an access request packet. Each slave 12a-12n decodes the access request packet and determines whether it has been selected to respond. If selected, the slave then responds appropriately by, for example, accepting data from the data bus in a Write operation, or driving data onto the data bus in a Read operation.

The foregoing system is exemplary of systems characterized by single-ended data transmission/reception over a bus consisting of multiple, impedance balanced signal lines. Data is transmitted at a relatively high frequency over these signal lines in relation to a single reference voltage. Such a system is susceptible to the timing errors and voltages described

above.

As will be seen hereafter, the present invention optimizes bus transmission conditions by minimizing overall timing and voltage errors. Operating margins for the system are improved accordingly, and data is communicated with greater reliability.

5 Fundamentally, bus systems operate in two phases; a calibration phase in which system operating parameters may be determined and a normal operation phase in which data is transferred at high speed in accordance with the parameters established during the calibration phase. Effective calibration of the bus system's operating parameters presents a number of concerns which will be discussed in detail below.

10 In a first general aspect, the present invention provides a system and method by which individual slave devices adjust their read and/or write timing to "slave" to a master clock signal. This aspect of the present invention is explained with reference to Figure 6.

Figure 6 further illustrates the relationship between master 11 and slave 12a within the context of the present invention. It is contemplated that all slaves 12a-12n of Figure 5 would be configured as is the slave illustrated in Figure 6, but for the sake of simplicity only one slave is shown. Further, considerable detail unrelated to the present invention has been omitted from the system shown in Figure 6.

Slave 12a comprises one or more receivers 60 and one or more transmitters 70 connected to data bus 30. Data sent from master 11 is communicated via data bus 30 to receivers 60. Data sent to master 11 from slave 12a is placed on data bus 30 by transmitters 70. The construction of receivers 60 and transmitters 70 is conventional and determined by the nature of the slave device and bus system.

Synchronous receipt of data by receivers 60 and synchronous transmission of data by transmitters 70 are respectively controlled by a Receive-clock signal (RCLK) and a Transmit-clock signal (TCLK). These signals are indicative of a class of clock signals gating data to/from the slave device referred to "internal read/write clocking signal." The RCLK signal is derived from the operation of a Receive Delay-Lock-Loop or Phase-Lock-Loop (DLL/PLL) circuit 61 and a Write Offset Register 62. While a DLL or PLL is presently preferred, any clocking circuit capable of accurately generating the internal read/write clock signal in relation to the master clock signal and the offset value may be used. The TCLK signal is derived from the operation of a Transmit DLL/PLL circuit 71 and a Read Offset Register 72.

As seen hereafter, both RCLK and TCLK are preferably derived in relation to the CTM and/or the CFM signals, but any clock signal might serve as the master clock signal.

The Receive DLL/PLL 61 and Transmit DLL/PLL 71 may be separately implemented, or implemented in a single clocking circuit using well understood design principles. For example, commonly assigned U.S. Patent Application 08/795,657 illustrates several possible implementations of a DLL/PLL circuit. U.S. Patent 5,614,855 also discloses a competent DLL circuit.

Write Offset Register 62 stores an offset value established during system calibration or initialization. The stored offset value defines a timing adjustment, as required, to RCLK in relation to the master clock signal (CTM).

For example, the individual timing characteristics of slave 12a in relation to the master clock signal are evaluated and adjusted during the calibration phase of operation, typically during system initialization. If the unadjusted application of the master clock signal to slave 12a results in a Write operation execution outside of the center of the data eye, see Figure 3B, then an offset value corresponding to the timing error δ (lead or lag) is calculated and stored in Write Offset Register 62. This offset value, when applied to the Receive DLL/PLL circuit 61 adjusts the timing of the RCLK signal such that data is accepted from data bus 30 in the center of the data eye, thereby compensating for any Write operation timing errors.

This timing error compensation is made individual to slave 12a, and is maintained, i.e., locked, by the DLL/PLL. The master clock signal remains fixed. No timing adjustment or compensation is required within master 11. The Write timing for each slave in the system may be individually adjusted in this manner.

The same holds true for the Read timing of each slave. The offset value stored in Read Offset Register 72 is similarly defined and applied to adjust, as required, the Read timing of slave 12a.

The block diagram of Figure 6 illustrates the relationship of the timing adjustment circuit(s) to the receivers and transmitters in a slave device, to a master device, and to a master clock signal. Figures 7 through 11 illustrate several embodiments of these circuits in additional detail. Each of these several embodiments is capable of providing an offset in a slave device DLL/PLL without consuming excessive power or occupying a significant area

within the slave device.

The circuit shown in Figure 7 takes full advantage of signals typically apparent in conventional DLL/PLL circuits. In the illustrated example, a 45° block from the DLL/PLL reference loop is acquired along with a 45° earlier version of the output clock taken from the fine loop phase mixer. These inputs are applied to a vector circuit 77 which may comprise two additional 45° blocks and a corresponding load. With this arrangement, vector circuit 77 outputs the original -45° input (C0), a 0° output from the first 45° block (C1), and a $+45^\circ$ output from the second 45° block (C2). The 0° output from the first 45° block is output as either RCLK or TCLK through a matched delay circuit 76.

The three outputs (C0, C1, and C2) from vector circuit 77 are applied to a phase mixer 75. By phase mixing the three signals, phase mixer 75 is able to generate an offset feedback signal varying between -45° and $+45^\circ$. The actual value of this offset feedback signal, which is returned as a feedback control signal to the DLL/PLL, is defined by the offset value stored in the Offset Register (62 or 72). The offset value is applied to Phase Mixer 75 through a digital-to-analog (DAC) converter 74. In this manner, system timing is conveniently adjusted using 45° pull-out sections of the DLL/PLL reference loop. Thus, this embodiment is able to adjust timing of RCLK/TCLK between -45° and $+45^\circ$. Of note, the timing adjustment provided by the circuit in Figure 7 are made in degrees such that the adjustment capability will scale in relation to the system operating frequency.

In contrast, the circuit shown in Figure 8 provides timing adjustment by changing an absolute time delay. The approach implemented by the circuit in Figure 8 can not be scaled with the operating frequency and is more susceptible to manufacturing process, voltage and temperature variations, but it is easy to implement and uses a relatively smaller device area.

In the circuit of Figure 8, the DLL/PLL receives a clock signal or stable frequency source in addition to the CTM and CFM signals which are applied to a transmit phase detector 88 and a receive phase detector 89, respectively. (Alternatively, CTM or CFM may be used as the frequency source). Transmit phase detector 88 also receives the TCLK feedback (Fbk) signal. Receive phase detector 89 similarly receives the RCLK feedback (Fbk) signal. The RCLK and TCLK signals are each output through a respective clock buffer chain 84 and 85.

The feedback signals RCLKFbk and TCLKFbk are adjusted by adding or subtracting

loads and thus adjusting the delay of a chain of invertors, 82 and 83, selected according to the offset value stored respectively in Write Offset Register 62 and Read Offset Register 72. The individual bits of the stored offset values may be configured to drive the enabling nodes and inverter(s) of corresponding MOS capacitors to effect a binary weighted variable load in the feedback paths of RCLKFbk and TCLKFbk to the DLL/PLL circuit.

Another technique for providing timing offset is illustrated by the circuit shown in Figure 9 which is analogous in operation to the circuit shown in Figure 8. This technique uses binary-weighted current sources to place an offset current into the input (front-end) differential pair of the PLL/DLL phase detector. See 88 or 89 in Figure 8. This offset current "pre-tilts" the input comparator one way or the other. This pre-tilt shifts the setup/hold window by adjusting the effective cross-point. The circuit shown in Figure 9 requires a very small area on the slave device, even smaller than the circuit shown in Figure 8. However, it should be recognized that the offset generated in this manner is really a voltage offset which only produces a corresponding timing offset when multiplied by the input edge rate. As a result, the offset is subject to not only process, voltage, and temperature variations, but also variation in the input-edge rate.

With reference to Figure 9, the output of binary-weighted current sources in a first chain of current sources 91 are summed in node A in accordance with a first set (A) of offset bits (1 . . . n). Similarly, the output of binary-weighted current sources in a second chain of current sources 92 are summed in node B in accordance with a second set (B) of offset bits (1 . . . n). The first and second sets of offset bits are stored in an Offset Register, such as the Read Offset Register 72 or the Write Offset Register 62 of Figures 6 and 8.

Another technique for generating a constant (in degrees) phase offset is illustrated in Figure 10. This technique employs a DLL utilizing delay elements with an adjustable supply voltage. In this embodiment, a reference loop control voltage 100 is set by a feedback reference loop 101 to an appropriate value such that the delay of a number of static, or semi-static, gates spans 0 to 180° of the clock period. Reference loop 101 receives an input clock signal and operates with phase detector 102 and charge pump 103. This feedback reference loop output signal essentially sets the supply of the static gates such that their RC time constant is an appropriate fraction of the clock cycle.

The reference loop control voltage (V_C) 100 is used to drive the peripheral loop

interpolators as well as a portion of the main clock (CLK) buffer 105 and feedback clock (FbkCLK) buffer 104. The FbkCLK signal is applied along with the input clock signal to phase detector 110. The output signal of phase detector 110 is applied to Interpolator 111 which also receives selected phase signals from reference loop 101.

5 By virtue of the fact that the delay-vs-supply characteristics of the reference loop buffers and the main and feedback buffers closely track one another, the offset introduced by changing the load capacitance of the feedback clock buffer 104 stays constant over supply and temperature variations. For example, assume that the clock cycle is T_c and the required offset is T_o . The reference loop will set V_c , such that $N \cdot R \cdot C_{ref} = T_c/2$, and offset control
10 register 106 will set the delay of the feedback clock buffer to differ from the main clock buffer by $T_o = M \cdot R \cdot C_{fb}$. Since voltage and temperature variations do not affect N , C_{ref} , M , C_{fb} , and since the reference loop adjusts R such that $N \cdot R \cdot C_{ref}$ always equals $T_c/2$, it follows that the ratio of T_o and T_c stays constant in the first order.

The specific implementation shown in Figure 10 uses digitally controlled capacitance
15 to adjust the delay of feedback clock buffer 104. The same result can be accomplished by changing the resistance of the buffers, i.e., controlling their width, or by multiplexing between two or more of the delay buffers. Both of these alternatives have the property that they generate an offset which stays constant relative to the clock period.

Like the exemplary circuits shown in Figures 7 and 10, the circuit of Figure 11
20 provides timing adjustment in degrees. However, in the embodiment shown in Figure 11, a full offset interpolator 121 is used in conjunction with a primary interpolator 120. Both interpolators receive a set of input or reference vectors from the DLL/PLL reference loop like, for example, those shown in Figure 7. The primary Interpolator 120 generates a feedback signal (CLKFbk) based on the reference vectors and the output of counter 123.
25 Counter 123 receives the output of phase detector 124 which compares the CLKFbk signal with a reference clock signal, such as CTM or CFM.

The output of counter 123 is also applied to adder circuit 125 which adds or subtracts, the offset value (n bits) stored in Offset Register 126. The adder result is then applied to Offset Counter 127, the output of which is applied to Offset Interpolator 121. Based on the
30 references vectors from the DLL/PLL reference loop and the Offset Counter output, Offset Interpolator 121 generates a clock signal (CLK).

Thus, Offset Interpolator 121 uses the same basic input vectors as the primary Interpolator 120 but has an offset register value added or subtracted from its mixing control value. The feedback clock (CLKFbk) used to close the control loop can be either the output of the primary Interpolator 120 (as shown), or that of Offset Interpolator 121, recognizing that difference that one output will have an offset register value opposite (i.e., the polarity is inverted) that of the other.

The implementation illustrated in Figure 11 provides an arbitrary phase offset, i.e., one ranging a full 360°. Since this offset is provided in degrees rather than absolute time (picoseconds of adjustment) the offset is stable with respect to PVT and frequency. Its size is comparable to that of the foregoing exemplary implementations.

Up to this point timing errors have been described in the context of read/write clock signals skewed in relation to data eyes. Using any one of the mechanisms described above, a properly adjusted read/write clock signal may be developed for each slave device to maximize clock signal margins in relation to data appearing on the data bus. For the sake of clarity, the examples illustrated above described data being communicated on one edge of the read/write clock. However, many contemporary bus systems communicate data between a master and one or more slaves using more than one edge of a clock signal or using multiple clocks having different phases. Alternatively, contemporary systems communicate multiple bits in relation to a single clock edge, but using different phase offsets. The use of multiple clock edges or multiple clocks at different phases results in an additional source of timing errors in the bus system, namely duty cycle errors. This problem is illustrated for an exemplary double data rate (DDR) system in Figure 12A and 12B.

In a DDR system, two bits of data are transmitted on one or more data bus lines during each clock cycle. These two bits are often referred to as "even" and "odd" data bits. Double data rate transmission may be accomplished in many ways, but two are illustrated here. In Figure 12A, a single internal clock (tclk) is used to set the duration of data transmission on the bus for both the even and odd data bits. In the example, even data is referenced to the high state of internal clock tclk and the odd data is referenced to the low state of tclk. The duty cycle of tclk is defined to be $T_{\text{high}}/T_{\text{cycle}}$. Further, since the "width" of the even data bit transmission cycle (or data eye) is defined by the duration of the high state of tclk, a second duty cycle, or a "data duty cycle" may be defined. The data duty cycle is the

width of the even data eye divided by the sum of the widths of the even and odd data eyes, i.e., $T_{\text{even}}/(T_{\text{even}}+T_{\text{odd}})$. It should be noted that $T_{\text{even}}+T_{\text{odd}}$ will typically be less than T_{cycle} due to signal jitter. The data duty cycle will be approximately equal to the clock duty cycle, although there may be slight differences if there are other odd/even offsets in the system. A similar DDR system might be constructed using a single clock, where the widths of the data eyes (odd and even) are set by the cross points of the true and complement forms of the clock rather than by the rising and falling edges of the clock

Figure 12B shows an analogous system that uses two clock signals, tclk_E and tclk_O . The falling (or rising) edge of tclk_O defines the beginning of the odd data eye and the falling (or rising) edge of tclk_E defines the beginning of the even data eye. For this system, the duty cycle of interest is actually defined by the difference between these two falling edges divided by the cycle time, rather than by the duty cycle of either clock signal. The data duty cycle may be defined as above.

The timing diagrams of Figures 12A and 12B are drawn with reference to data transmission clock (tclk). Similar diagrams might be drawn with reference to a data reception clock (rclk). However, when drawn with reference to the data reception clock, the right half of the even data eye and the left half of the odd data eye are encompassed by the high state of the rclk . As with the transmission clock example illustrated above, a differential reception clock with timing set at the crosspoints, or two single ended clocks with falling (rising) edges might be used to establish the requisite data reception eyes.

The present invention may be used to properly adjust duty cycle(s) in relation to a transmission and/or a reception clock. Further, the present invention has application beyond DDR systems. For example, the present invention might be adapted for use in a Quad Data Rate (QDR) system in which timing for data exchange is set by four clocks spaced 90° apart. In QDR systems there are actually four different data duty cycles, each data duty cycle being defined as the width of an eye for a given data bit divided by the width of all data eyes. One of ordinary skill in the art will see that the following principles may be applied to any N-Data Rate system, where N is a whole number.

No matter the actual number of clock signals or edges, the overall timing margin of the bus system is limited by the width of the smallest data eye defined by a duty cycle. Thus, for maximum timing margins, the data duty cycle should be as close to $1/N$ as possible, where

N is the number of duty cycle defining clock signals or edges in the system.

However, the variable effects described above combine to skew duty cycle data eyes. Offsets in the system clock or in the internal clock generation circuits will result in duty cycle timing errors which reduce timing margins and compress overall system timing requirements. Thus, adjustment of the clock signals defining erroneous duty cycles is required to optimize system bus performance.

Read duty cycle adjustment and/or write duty cycle adjustment may be accomplished in a manner similar to that discussed above in relation to read/write clocks. For example, as shown in Figure 13, a write duty cycle offset register 63 and/or a read duty cycle offset register 73 may be added to the structure shown and described in relation to Figure 6. The Receive DLL/PLL buffer 61 and the Transmit DLL/PLL buffer 71 are modified to accept and use the read/write duty cycle offset values stored in registers 63 and 73. These read/write duty cycle offset values are used to adjust the duty cycles of the clock signals produced by these buffers.

Duty cycle adjustment does not necessarily require active clock recovery, as provided by the DLL/PLL. Duty cycle adjustment might equally apply to a system where skews between internal and external timing points are compensated outside the slave devices, outside the master, or outside both the master and slave devices.

In other words, duty cycle adjustment may be accomplished not only by use of offset registers located on individual slave devices, but also by use of one or more global offset register(s) resident in the master. A single "mean" duty cycle offset value might be stored in the global register and communicated to individual slave devices, or a plurality of individualized duty cycle offset values might be stored and communicated on an individual basis to respective slave devices or group of slave devices. The one or more duty cycle offset register(s) might alternatively be stored outside the master or slave devices.

One embodiment of a duty cycle adjustment circuit is shown in Figure 14. This circuit, preferably residing within the DLL/PLL buffer circuit, comprises a current mode output digital-to-analog converter (DAC) 140 receiving the duty cycle adjustment values from read/write duty cycle offset register (63/73). In response to the duty cycle adjustment value received, DAC 140 produces two current signals I_{OFFSET} and I_{OFFSET} which are applied to duty cycle adjustment circuit 141

In a nominal case, wherein no duty cycle adjustment is required, I_{OFFSET} and I_{OFFSET} are equal and the differential input signal clkin passes through duty cycle adjustment circuit 141 unchanged to form output signal clkout . The clkout signal is then converted by a differential to CMOS converter circuit 142 to form a single ended clock for uses in the receiver or transmitter circuits. Alternatively, differential to CMOS converter circuit 142 may be replaced by a differential buffer/amplifier which would produce a differential clock signal of appropriate strength to drive the receiver or transmitter circuits.

If there is some difference in the current signals I_{OFFSET} and I_{OFFSET} , the differential waveforms clkout and clkout will be shifted in relation to one another. This shift in relationship will change their differential duty cycle. As presently preferred, the ratio $(I_{\text{OFFSET}}, I_{\text{OFFSET}}) / I_{\text{OUT}}$ will be relatively constant resulting in better independence from voltage and temperature drifts. The duty cycle change will be reflected in the output clock signal (CLK) produced by differential to CMOS converter 142.

The above circuit performs duty cycle adjustment in an "open-loop" manner. That is, no feedback mechanism exists between the corrected clock signal and the duty cycle adjustment circuit. Accordingly, the system must either have sufficient timing margin to work following a single calibration cycle during initialization, or the system must perform periodic re-calibrations.

A presently preferred embodiment of the duty cycle adjustment circuit 141 of Figure 14 is shown in Figure 15. The circuit shown in Figure 15 receives I_{OFFSET} , I_{OFFSET} , I_{OUT} , clkin and clkin as inputs, and generates clkout and clkout as outputs. Relationships between these signals are further illustrated in Figure 16.

Another exemplary embodiment of the duty cycle adjustment circuit is shown in Figure 17. The circuit like the one described in Figure 15 comprises a DAC 170 receiving the duty cycle offset values from duty cycle offset register 63/73 and duty cycle adjustment circuit 172 receiving clkin and clkin and outputting clkout and clkout to differential to CMOS converter 173 which produces the output signal (CLK).

However, this embodiment further comprises a feedback path formed by duty cycle integrator 171 and CMOS to differential converter 174. One embodiment of duty cycle integrator 171 is shown in Figure 18.

In addition to I_{OFFSET} and I_{OFFSET} , duty cycle integrator 171 receives a differential

feedback clock signals \overline{FBin} and $FBin$. The differential feedback clock signals \overline{FBin} and $FBin$ steer the bias current (I_o) 180 using differential pair 181a/b. If the feedback clock has a 50% duty cycle, these two current signals will be equal and the voltage difference at nodes c_o and $\overline{c_o}$ will not change. If, however, the duty cycle is not 50%, then a voltage difference will rise or fall as the current is integrated into capacitors 182a/b.

The output of this duty cycle integrator shown in Figure 18 is applied to the duty cycle adjustment circuit of Figure 19 where it steers current in the differential pair 190a/b. As with the duty cycle adjustment circuit described in Figure 15, the difference in currents I_a and I_b will shift the $clkout$ and \overline{clkout} currents one to another, thereby changing the duty cycle.

In principle, this duty cycle adjustment scheme should produce the desired clock signal duty cycle without the effect of the duty cycle adjustment value applied from the duty cycle offset register. In practice, however, device mismatches in the duty cycle integrator (171 in Figure 17 and Figure 18) and in the CMOS to differential converter (174 in Figure 17) will not be compensated out, so the optimum adjustment value for the duty cycle offset register will sometimes be nonzero. Current mirrors 185a/b of Figure 18 add the differential offset current I_{OFFSET} to the integration nodes c_o and $\overline{c_o}$. This will cause the system to reach equilibrium for a \overline{FBin} duty cycle of other than 50%. Thus, by changing I_{OFFSET} based on the duty cycle adjustment value stored in the duty cycle offset register (63/73), the duty cycle of the clock (CLK) can be properly adjusted. Any value for I_{OFFSET} and $\overline{I_{OFFSET}}$ will require a compensating duty cycle adjustment on \overline{FBin} and $FBin$ to be made by the feedback loop formed by duty cycle adjustment circuit 172, differential to CMOS converter 173, CMOS to differential converter 174, and duty cycle integrator 171. As with the embodiment shown in Figure 15, the ratio of $(I_{OFFSET}, \overline{I_{OFFSET}})/I_o$ is relatively constant.

The precepts and relations taught by the exemplary circuits above, may be generically extended and applied to systems having N clocks producing N-Data Rate signals. Conceptually this application is illustrated in Figure 20 in which a plurality of duty cycle offset values 201 (a . . . n) are respectively applied to duty cycle adjustment circuits 202 (a . . . n) to properly adjust input clock signals clk_{in} (a . . . n). In this embodiment, each clock signal is delayed by a corresponding duty cycle offset, but a single mean duty cycle offset value might be applied to each duty cycle adjustment circuit.

In one preferred implementation, each duty cycle adjustment circuit 202 in Figure 20

comprises the circuit shown in Figure 21. This circuit's behavior is analogous to that of the circuit shown in Figure 8. In the circuit of Figure 21, clock signal delay is adjusted by adding or subtracting loads from a chain of inverters 210, which are selected according to the duty cycle offset value stored in duty cycle offset value register 211. By adjusting the relative delays of the N delay adjustment circuits 202, the size of the N-data eyes can be individually defined.

A variation on this scheme would be to use N-1 buffers rather than N, wherein the size of the Nth data eye corresponding to the Nth clock is defined by moving all the other clock eyes relative to the this last clock. In another related embodiment, the constant delay buffers of Figure 10 would be used instead of the inverters of Figure 8. This scheme would have the advantage that delay adjustments would not change with environmental conditions.

In yet another embodiment drawn in relation to a DDR system, the circuit shown in Figure 22 is used to provide appropriate delay adjustments. The circuit of Figure 22 is identical to that of Figure 17 except that the DAC and the duty cycle offset port in the duty cycle integrator have been replaced. The offset is provided by skewing the differential feedback clock FBin1 using delay adjustment circuits 220a/b receiving duty cycle adjustment values from registers 221a/b before feeding it as FBin2 into the duty cycle integrator 171. The delay adjustment circuits 220a/b may be similar to the circuits shown in Figures 8 or 10.

The embodiment shown in Figures 20 and 21 is designed to effect duty cycle adjustment in a slave device. However, it is also possible to adjust the duty cycle on the master using similar schemes and circuits. Of course, master resident circuits to accomplish duty cycle adjustment will consist of a single duty cycle adjustment register storing a single "mean" duty cycle adjustment value, or a plurality of registers storing duty cycle adjustment values for each respective slave device. In the later implementation, the master selects the appropriate duty cycle adjustment value on the basis of the slave device having data written to it or having data read from it.

Figure 23 illustrates another embodiment of a duty cycle adjustment circuit correcting multiple clocks. In this scheme, the individual clocks are produced from differently phased clock signals ($\phi 1$, $\phi 2$, $\phi 3$) coming from Voltage Controlled Oscillator (VCO) or delay line 230. (Any reasonable number of phased clock signals may be used, but three are shown in this example). Based on the duty cycle adjustment values stored in duty cycle registers 233

(a . . . n), phase selectors/interpolators 232 (a . . . n) adjust the exact timing of the output clock edges in relation to a nominal value. Movement of these clock signal edges change the sizes of the corresponding data eyes. In another variation of this scheme, phase
5 selector/interpolator operation is controlled both by the duty cycle adjustment value and the overall phase adjustment register used to set the phases of all the internal clocks to desired relationships with respect to a reference clock.

In addition to timing errors, voltage errors frequently plague bus systems. Voltage errors and their effects were illustrated in the discussion of Figures 4A and 4B above.

In a second general aspect, the present invention provides a system and method by
10 which individual slave devices adjust or compensate the voltage of data received from the data bus, and/or adjust the voltage/current of data being driven onto the data bus. Analogous to the timing adjustment techniques described above, voltage adjustment takes place on a slave by slave basis.

During voltage adjustment, the output voltage swing is properly set and any voltage
15 offset in the received data is compensated. These two functions may be accomplished in many specific ways. Fundamentally, after the master output swing and input levels are optimally established, the resulting signal levels are considered reference, and both slave input offsets and slave output voltage/current are adjusted to correspond to these references.

Figure 24 illustrates a basic approach to voltage adjustment in which signals received
20 from data bus 30 at the front end of a receiver 60 (only a portion of which is shown) are input to a differential compensating amplifier 240. The write data voltage levels are compared to V_{ref} and adjusted in accordance with a write voltage offset value stored in voltage offset circuit 241. Similarly, the output current of driver 242 is adjusted in accordance with read voltage offset value stored in a current control circuit 243. This example assumes a slave
25 output scheme based on controlled current source output drivers, but is readily adapted to other forms of output drivers.

In the approach illustrated in Figure 24, the master contains the more extensive logic and control circuitry required to calibrate the output current level and input voltage offset for each slave in the system. As there are typically many more slaves than masters in a system,
30 the overall system impact of the voltage calibration and adjustment components is minimized. Further, slave die space is conserved.

The exemplary circuits shown in Figures 7 through 11 illustrate several embodiments in which one or more offset values are used to adjust read/write timing to the center of a prescribed data eye. By adjusting read/write timing on a slave by slave basis, the effects at each slave can be compensated for individually and independently. Further, the exemplary circuits shown in Figures 13 through 23 illustrate several embodiment in which one or more offset values are used to adjust read/write clock duty cycles. In order to adjust read/write timing (including duty cycle) on a slave by slave basis, the one or more offset values must be determined and stored for each slave device.

The process of determining and storing the slave offset value(s) is performed during the calibration phase of system operation. The calibration phase typically occurs during system initialization, but may be performed otherwise. For example, calibration may be performed periodically or upon detection of some threshold number of bit errors. The actual determination of the timing offset values may be done using many different techniques. Several techniques are described below.

One technique is referred to as 90° calibration, and it requires the use of a DLL/PLL on the master capable of shifting its clock output by 90° . Together, the block diagram of Figure 25 and the timing diagram of Figure 26 illustrate this technique which is used to calibrate the master-transmit-to-slave, or the write path.

In Figure 25, master 11 comprises a transmit DLL/PLL having a normal (0°) output clock signal and a calibration shifted (90°) internal transmit clock signal. During the calibration phase, master 11 selects the calibration shifted output clock, and then transmits a data sequence to receiver(s) 60 in slave 12a. (Some considerations for a proper calibration phase data sequence are discussed below). Given a data eye corresponding to the normal output clock from the transmit DLL/PLL of master 11, a properly centered slave receive clock would transition in the center of the data eye. See signal A in Figure 26. However, since the calibration shifted internal transmit clock signal offsets data by 90° , a centered transition of the slave receiver clock "A" will now occur at the center of the data transition region instead of the center of the data eye. In cases where the slave receiver clock is too early, signal A' in Figure 26, or too late, signal A" in Figure 26, the transition will not occur at the center of the data transition. Assuming that the data pattern used during calibration has a balanced number of 0 to 1 and 1 to 0 transitions, then this result allows slave receiver 60 to

operate as a phase detector.

For example, assuming a data transition from a "0" to "1" on the data bus line into the slave receiver, the early occurring slave receiver clock transition A' would consistently produce a "0" output. Similarly, the late occurring slave receiver clock transition A" would consistently produce a "1" output. Thus, the data output by the slave receiver can be used to determine phase information during the calibration phase. The slave receiver data derived from this calibration process can be stored in the slave and returned to the master during a subsequent read operation.

The foregoing capabilities can be used by system designers to define an appropriate write offset value. Many different algorithms may be implemented as a matter of routine design choice which result in a "centering" write offset value in a minimum of time and resources. For example, a simple single data transition might be written from master 11 to slave 12a in a large block of data, say 128 bits consisting of 64 ones followed by 64 zeros. These bits are stored in the slave and read back to the master. The master determines where in the data block a one-to-zero transition occurred, and uses this information to increment or decrement the read offset value. This sequence of steps continues until the offset value dithers back and forth between "0" and "1" (i.e., "toggles") with each iteration at which point a centering offset value has been obtained.

Conceptually, the foregoing technique extends conventional DLL/PLL locking loop techniques to implement timing offset control by building a distributed pseudo-DLL using the slave receivers as phase detectors. Thus, assuming the presence within the master of a 90°-shiftable DLL clock, the additional hardware required to implement timing calibration is minimal. Once the output of the data receiver(s) toggle, the distributed loop can be "locked," and the timing of the master output clock returned to normal (0°).

A similar approach to slave transmitter clock calibration (i.e., read offset value determination) can be readily discerned from the foregoing. In this approach, the internal receive clock is shifted by 90° and the master data receivers function as phase detectors. The process of transmitting a block of data, looking for tell-tale data transitions, adjusting the offset value, and repeating until determination of the optimal read offset value, is performed as explained above, except the consideration that data flow is reversed between the two processes. Figure 27 illustrates this approach and the presence of a Receiver DLL/PLL 145

having an output clock which is shiftable by 90° .

The circuits shown in Figures 25 and 27 require that the transmit and receive DLL/PLL on the master incorporate circuits providing the 0° and 90° shifted clock signals. However, such area consuming circuits are not required in the more numerous slave devices, and such phase-shifted clocks are easily available in many DLL/PLL designs. Thus, these configurations accomplish the purposes of the present invention with reduced overall system costs.

Another approach to timing calibration uses a "scanning window," as illustrated in Figure 28, to determine an appropriate offset value for slave read or write timing. During calibration the offset interpolators are scanned across a data window as the master searches for a transition from a passing region to a failing region, i.e., a data transition from 0-to-1, or 1-to-0. One way to accomplish this scanning effect is to provide a register in the master (or slave) DLL/PLL having a range of offset values. By scrolling through the range of offset values and applying each value to the read/write clock, the clock transition will move in relation to the data eye. One offset value will find the leading edge of the data eye and another offset value will find the lagging edge of the data eye. After the master has located both edges of the passing window of the data eye and identified the two corresponding offset values, the master can then take the two offset values and interpolate half-way between them to find the center position for the read/write clock relative to the data eye.

Once an appropriate offset value has been determined, it is written to the corresponding offset register in the slave. Alternatively, the offset scanning may be done by offset interpolators in the slave device. However, the first approach of locating the required interpolators in the master saves overall area in the system.

As illustrated in Figure 24, one or more offset values are used to adjust slave read/write voltages in relation to V_{ref} . By adjusting the read/write voltages on a slave by slave basis, V_{ref} is maintained as a reference and voltage effects are compensated at a local level rather than forcing a system level compensation scheme. In order to adjust the read/write voltages on a slave by slave basis, the one or more offset values must be determined and stored in the voltage offset circuit and current control circuit of Figure 24, or equivalent circuits.

The process of determining and storing the voltage offset value(s) is performed during

the calibration phase like the process for determining and storing timing offset value(s). The actual determination of the voltage offset values may be done using many different techniques. Several techniques are described below.

5 The first technique for calibrating slave voltages, i.e., determining the voltage offset values, is illustrated in Figures 29 and 30. Analogous to the timing calibration scanning window approach, this technique uses a scanning window to calibrate slave voltages. That is, the scanning window feedback mechanism is applied to voltages instead of timing.

10 The circuit shown in Figure 29 assumes a voltage calibration directed to the input (or write) voltage swing for data transmitted from the master to the slave. As data is written from master 11 to a receiver in slave 12a during calibration, its voltage level is compared in 290 with an externally supplied Vref signal. The comparison result is feedback through control logic 291, Vref register 292, and a DAC 293, to an offset-port of a stabilizing (1X) amplifier 294. The nature of node "a" in Figure 29 is determined by the nature of the Vref signal. Where Vref is an externally generated, or otherwise voltage controlled signal node "a" will
15 comprise an adder circuit or other means for combining the two signal paths. Alternatively, where Vref is generated internal to the slave device by the value stored in an offset register, the adder circuit may be omitted.

20 As with the scanning window approach described above, high and low pass/fail transition points are identified. Vref on the slave is set in accordance with a final adjustment offset value located half way between the offset values corresponding to the high and low pass/fail transition points.

25 In another technique write voltage calibration is accomplished through the use of voltage offset cancellation loops located in the slave receiver(s). This technique is illustrated in Figure 31 in which master 11 actually drives the slave's Vref. Master 11 comprises a switch 310 between a nominal Vref generator 311 and a Vol voltage source 312. During write voltage calibration master 11 switches the slave Vref to Vol, and simultaneously drives Vol on its output drivers 315.

30 Slave 12a is placed in write offset calibration mode wherein each slave receiver compares the received data signal at Vol with the "master" Vol signal applied through the Vref signal line. This comparison takes place in voltage cancellation loop 318 which consists of a slave receiver acting as a comparator 317 and offset cancellation circuit 319. Voltage

offset values are applied (added and subtracted) through offset cancellation circuit 319 of the slave receiver until its output toggles at which point the offset loop is locked. Offsets due to manufacturing defects in the slave receiver and/or I*R drops present in the data bus are eliminated in this fashion.

5 In another adaptation of the circuitry shown in Figure 31, a binary master current control value is simply right-shifted by one bit to half its value. The resulting value is applied to output driver 315. The slave accordingly compares the output of driver 315, V_{ol} at half its normal current, to V_{ref} . An offset cancellation loop is run as above until the output toggles.

10 Read voltage output swings for the slave are similarly calibrated. For example, in Figure 32 a current control register 320 in slave 12a is right-shifted by one bit in order to drive half the nominal output value from a slave transmitter. A corresponding receiver in the master samples the output level of the returned data signal and compares it to V_{ref} . An up/down signal resulting from this comparison is feedback to slave 12a via a feedback signal line. The up/down signal is applied to increment or decrement a slave current control value in
15 a current control register 321 until the output of the master receiver toggles at which point the output swing loop is locked. This loop also compensates for DC channel resistance since the "sense" element in the path, i.e., the master receiver, is the same element used to detect read data transmissions.

20 Alternatively, the read output voltage swing may be calibrated using a circuit like the one shown in Figure 33. Here, slave 12a transmits both a "1" and a "0" on different data bus lines 335a and 335b. Master 11 comprises a precision resistive divider 330 which receives these signals and combines them to form an output voltage of $V_{swing}/2$. This output voltage is then compared to V_{ref} in a master data receiver. The result of this comparison is then sent back to slave 12a as an up/down signal and applied to a current control register 331 which is
25 incremented or decremented accordingly until the output of the "comparator" data receiver in the master toggles between 0 and 1.

30 As with timing and voltage calibration, there must be a way of determining the appropriate values to program into the duty cycle adjustment registers. This can be readily accomplished using a modified version of the scanning window illustrated in Figure 28. The modified scanning window is illustrated in Figure 34. Instead of a single set of curves corresponding to varying values of the offset register, there are multiple sets, each

corresponding to a different value for the duty cycle adjustment offset. Each set has the same duty cycle, but differing phases, depending on the duty cycle adjustment offset value. As before, the duty cycle adjustment offset values are scrolled through to find the leading and lagging edges of the data eye. However, for duty cycle calibration, this procedure must be
5 run N times for an N-data rate system in order to find the edges of each eye.

The example shown in Figure 34 illustrates this procedure for a DDR system, where the scrolling is performed twice, once to find the edges of the even eye and once to find the edges of the odd eye. The procedure is repeated for each value of the duty cycle offset register. The device chooses the duty cycle offset values which make the width of the even
10 and odd eyes most closely equal.

If the relationships (i.e. the mapping) between duty cycle adjustment offset values and the corresponding eye sizes are known, a second method can be employed. Namely, the size of each eye is measured using nominal duty cycle offset values, then the appropriate register values are chosen to make the eyes of equal size based on the known the relationships.

15 If the relationships are not known, they can be estimated by setting the duty cycle adjustment offset values to the extremes of their ranges and then scrolling and measuring the sizes of the eyes. Appropriate values can be chosen by interpolation between the measured duty cycles at the extremes.

Another approach would be simply to measure the overall size of the composite eye,
20 and choose the duty cycle offset register settings that made this size the largest.

Until now, timing (including duty cycle) and voltage adjustments have been discussed as separate phenomenon. While various adjustment mechanisms have been described which address these problems separately one of ordinary skill in the art will recognize that timing adjustments and voltage adjustments are better viewed as a related family of operating system
25 parameters. Effective bus optimization seeks to maximize both timing and voltage margins, although improvements to one or the other will remedy different system performance problems. Recognizing the interplay between signal timing and signal voltage requirement, the concept of signal equalization will now be addressed.

Signal equalization parameters can also be adjusted to increase voltage margins for
30 data signals on the system bus. Equalization involves dynamically changing the drive strength of a channel output driver to compensate for noise signals on the bus. Noise signals

may arise from many sources including adjacent channel crosstalk, or residual or undesired signal reflections on the bus. No matter their nature or origin, noise signals cause signal voltages to vary from one clock cycle to another. Compensation for signal voltage variations due to residual signals on the channel is referred to as "temporal equalization."

5 Compensation for signal voltage variations due to inductive coupling from neighboring channels is referred to as "cross-talk (or spatial) equalization."

Temporal and cross-talk equalization are discussed separately below. It should be noted that the circuitry to accomplish both forms of equalization may be resident in a master transmitter or in respective slave transmitters.

10 Figure 35 illustrates a signal waveform on a hypothetical channel that results from an unequalized transmission of data having a logic pattern 0, 1, 1, 0. The voltage on the channel rises to VOH during transmission of the first logical 0 and then drops toward VOL during transmission of the first logical 1. As shown, the voltage on the channel does not reach VOL during transmission of the first logical 1 and instead reaches a local minimum 200mV above
15 VOL. By contrast, the voltage on the channel drops 100 mV below VOL during transmission of the second logical 1. Finally, the voltage on the channel reaches a local maximum 200mV below VOH during transmission of the final second logical 0.

The foregoing illustrates how signal voltage on a channel is affected by prior transmissions on the same channel. In general, a logical 1 that follows transmission of a
20 logical 0 is less likely to reach VOL than a logical 1 that follows transmission of another logical 1. Similarly, a logical 0 that follows a logical 1 is less likely to reach VOH than a logical 0 that follows another logical 0. Both these effects result in reduced voltage margin at the receiver, making the system more susceptible to errors caused by noise and other margin-reducing effects.

25 Figure 36A illustrates an output driver 700 that includes temporal equalization circuitry according to one embodiment of the present invention. A data signal, Data_j, is used to gate a weighted driver 701. When Data_j is a logical 1, the weighted driver 701 is turned ON to a degree determined by a current control value (CCTL) in register 703 so that a current I_{SIG} flows through driver 701. Weighted equalization drivers 702A-702K are similarly gated
30 by respective prior versions of the data signal (Data_{j-1}, Data_{j-2}, ..., Data_{j-K}) to sink equalization currents I_{EQ1} through I_{EQK}. Thus, the total current that flows through R_{TERM} is

given by: $I_{OL} = I_{SIG} + I_{EQ1} + I_{EQ2} + I_{EQK}$, with each of the I_{EQ} terms being controlled by equalization coefficients stored in respective equalization registers 704A-704K. Because the output voltage V_{OUT} is equal to

$V_{TERM} - I_{OL} * R_{TERM}$, V_{OUT} can be equalized to compensate for prior outputs by appropriate setting of equalization coefficients.

Figure 36B illustrates an embodiment of output driver 700 in greater detail. As shown, the weighted driver 701 includes N binary weighted transistors (1x, 2x, ... 2N-1x) so that I_{SIG} is given by $Dataj * CCTL * I_{UNIT}$, I_{UNIT} being the current through the 1x transistor when active.

Data history generator 705 receives Dataj and a transmit clock signal, tclk, and generates K delayed data signals, Dataj-1 through Dataj-K. In one embodiment, a new data value is transmitted at each rising edge and each falling edge of tclk. Thus, the delayed data signals are generated by passing Dataj through a sequence of flip-flops 706A-706K that are alternately clocked by falling and rising edges of tclk. By this arrangement, flip-flop 706A outputs Dataj-1, flip-flop 706B outputs Dataj-2 and so forth to flip-flop 706K which outputs Dataj-K. In an alternative embodiment in which data is transmitted on only one clock edge per cycle of tclk (i.e., one data value per clock edge instead of two), flip-flops 706A-706K may be clocked by same edge of tclk.

Equalization driver 702A includes a multiplexer 709, a set of additive logic gates 712A-712R and corresponding binary weighted transistors (1x, 2x,..., 2R-1x), and a set of subtractive logic gates 711A-711R and corresponding binary weighted transistors -1x, -2x,..., -2R-1x). In the embodiment shown in Figure 36B, each of the equalization registers 704A-704K contains a signed value formed by a coefficient sign (bit S) and a coefficient magnitude (e.g., C1, C2, ..., CK). Referring specifically to equalization register 704A, the coefficient sign is used to select between inverted and non-inverted versions of the data value Dataj, while each bit of the coefficient magnitude is input to a logic gate pair. Each logic gate pair consists of an additive and a subtractive logic gate both having a multiplier that corresponds to the bit position of the coefficient magnitude, but with opposite signs. For example, bit 1 of the coefficient magnitude is input to logic gates 712A and 711A which, depending on the state of Dataj-1, activate the 1x and the -1x transistors, respectively. Similarly, bit 2 of the coefficient magnitude is input to logic gates 712B and 711B to control activation of the 2x

and $-2x$ transistors, and bit R of the coefficient magnitude is input to logic gates 712R and 711R to control activation of the $2R-1x$ and $-2R-1x$ transistors. Although Figure 36B indicates that the coefficient magnitude includes at least three bits (i.e., $R=3$), the coefficient magnitude may include more or fewer than three bits without departing from the scope of the present invention.

Reflecting on the operation of the equalization driver 702A, it can be seen that when the magnitude coefficient in register 704A is zero, all transistors controlled by subtractive logic gates 711A-711R are activated and all transistors controlled by additive logic gates 712A-712R are off. This is true regardless of the state of Dataj-1 or the sign bit, S.

Consequently, when the coefficient magnitude is zero, the equalization current, I_{eq1} is becomes $2R * I_{UNIT}$. When the coefficient magnitude is at a maximum (i.e., all bits set) and Dataj-1 is a logical 1 and the coefficient is positive (i.e., sign bit equal 0), then all the transistors controlled by the subtractive logic gates 711A-711R and all the transistors controlled by the additive logic gates 712A-712R are activated so that the equalization current becomes $2R+1 * I_{UNIT}$. Conversely, when the coefficient magnitude is at a maximum and Dataj-1 is a logical 0 and the coefficient sign is negative, then all the transistors controlled by the subtractive logic gates 711A-711R and all the transistors controlled by the additive logic gates are off so that the equalization current is turned off. More generally, the current I_{EQ1} is given by the expression:

$$I_{EQ1} = 2R * I_{UNIT} + (C1 * 2R) * \text{Polarity}(\text{Dataj-1}) * I_{UNIT},$$

where C1 may be positive or negative and where $\text{Polarity}(\text{Dataj-1}) = 1$ if Dataj-1 is 1; and -1 if Dataj-1 is 0. The currents drawn by equalization circuits 702B-702K are similarly controlled by coefficients C2-CK. By this arrangement, each of the equalization circuits allows current to be increased or decreased relative to $2R * I_{UNIT}$ based on respective coefficients and delayed data values. Thus, the overall current IOL is given by the expression:

$$I_{OL} = I_{SIG} + I_{EQ},$$

$$\text{where } I_{EQ} = 2R * K * I_{UNIT} + C1 * 2R * \text{Polarity}(\text{Dataj-1}) * I_{UNIT} +$$

$$C2 * 2R * \text{Polarity}(\text{Dataj-2}) * I_{UNIT} +$$

$$\vdots$$

$$\vdots$$

$$\vdots$$

$$CK * 2R * \text{Polarity}(\text{Dataj-k}) * I_{UNIT}$$

By selecting the current $2R \cdot K \cdot I_{UNIT}$ to correspond to the desired high voltage level on the channel (VOH), the coefficients in the equalization registers can be used to effect a current swing above and below the nominal current used to produce VOH and above and below the nominal current used to produce VOL. These current swings can be used in turn to overdrive or underdrive the channel, compensating the output voltage for past output levels. Note that the current I_{UNIT} drawn by the 1x transistor in the equalization drivers may be different from the current I_{UNIT} drawn by the 1x transistor in the weighted driver 701.

Although Figures 36A and 36B illustrate a pull-down circuit for equalizing the channel voltage, a combination of pull-up and pull-down circuits may be used in an alternative embodiment. For example, a set of weighted transistors coupled between V_{TERM} and the output of driver circuit 700 may be used to pull up the output signal in proportion to a negative equalization coefficient and a corresponding set of weighted transistors may be used to pull down the output signal in proportion to a positive equalization coefficient. Generally, any circuit for adjusting channel voltages may be used without departing from the scope of the present invention.

As mentioned above, cross-talk equalization involves equalizing a channel voltage to compensate for cross-coupled signals from neighboring channels. The circuits shown in Figure 36 and 37 may be modified to provide cross-talk equalization. Referring to Figure 36A, for example, the data history generator 705 may be removed and the outputs of neighboring channels may be coupled to the inputs of equalization drivers 702A-702K. By this arrangement, equalization currents I_{EQ1} - I_{EQK} may be generated based on the state of neighboring channels and weighted by the coefficients stored in equalization registers 704A-704K. As with temporal equalization, a combination of weighted pull-up and pull-down circuits or other circuits for adjusting channel voltages may be used to perform cross-talk equalization. As discussed above, a given device may include both cross-talk equalization circuitry and temporal equalization circuitry.

The foregoing examples of temporal and cross-talk equalization have been drawn to output driver circuit, or transmitter-side circuits. However, such circuit may be incorporated receiver-side.

For example, Figure 37 illustrates a bus receiver 800 with equalization circuitry according to one embodiment of the present invention. Incoming data, Data_j, is summed with

an equalization offset 816 in analog adder 817, generating an equalized data value, DEQ, for comparison with VREF. The equalization offset 816 is generated by adding and subtracting equalization coefficients C1-CK according to the state of previously received data values, Dataj-1-Dataj-K, respectively.

5 A data history generator 705 receives the output of comparator 830 and generates the data history values, Dataj-1, Dataj-2, ...Dataj-K. The data history values are used to select, via multiplexers 811A-811K, between positive and negative versions of respective equalization coefficients C1EQ-CKEQ stored in equalization registers 804A-804K. As with the equalization coefficients discussed in reference to Figure 36B, equalization coefficients
10 C1EQ-CKEQ may be positive or negative values. As shown in Figure 37, a negative version of the content of each equalization register 804A-804K is generated by a respective two's-complement generator 809A-809K. Any number of circuits for generating negative versions of the equalization coefficients may be used in alternative embodiments. Also, one's-complement circuitry may be used in alternative embodiments instead of two's complement
15 circuitry.

 A digital adding circuit 814 receives the output from each of the multiplexers 811A-811K and provides a sum of coefficients to digital-to-analog converter 815 which generates the equalization offset 816. In an alternative embodiment, separate digital to analog
20 converters are used to convert the outputs of multiplexers 811A-811K to respective analog values. The analog values are then combined with the incoming data value, Dataj, in analog adder 817. In this embodiment, adding stage 814 may be omitted, reducing the amount of time required to provide a valid offset value at adder 817. In another alternative embodiment, adder 817 is used to add the equalization offset 816 to Vref instead of to the incoming data. In this case, the equalization offset is generated with reverse polarity.

25 In yet another embodiment, of the bus receiver, analog rather than digital circuitry is used to perform equalization. Sample and hold circuitry is used to capture past data signals (i.e., Dataj-1- Dataj-k). The amplitude of the captured signals are weighted by equalization coefficients C1EQ - CKEQ from registers 804A-804K, then input to adder 817. Cross-talk equalization is also accomplished in this manner, except that neighboring signals are
30 weighted by the equalization coefficients instead of prior data signals on the same signal path.

 Equalization coefficients may be determined using the techniques described above for

determining voltage offset values. See Figures 24 and 29-31 and related discussion above. Referring to the scanning window feedback technique shown in Figure 29, for example, a slave may write a sequence of patterns of successive bits (e.g., 101, 001, 010, 110...) to a master to allow the master to determine the signal margin in the final bit of each pattern. For
5 example, the master may determine that the voltage on the channel is 200mV above VOL in the final bit of the pattern 01 and 200mV below VOH in the final bit of the pattern 10 and provide a coefficient that contributes $\pm 200\text{mV}$ to the slave device.

Thus, by gauging the effect of toggled bits in different positions in the pattern, temporal equalization coefficients may be determined, fed back to the slave and installed in
10 the temporal equalization registers within the slave's transmitter or receiver. Equalization coefficients for the master's transmitter may be determined in a similar manner with the slave returning margin measurements to the master for the master to determine its own coefficients.

In an alternative embodiment, each bit in each equalization register may be set during transmission of the sequence of bit patterns and then reset for transmission of the same
15 sequence. Margin measurements may be made by a receiving device (e.g., a master if a slave's transmitter is being equalized) and used to determine whether the equalization bit should remain set. If the margin is improved, the bit under test is set. Otherwise the bit is reset. By successively testing the effect of each bit in the equalization register, moving from most significant bit to least significant bit, the appropriate equalization value may be
20 determined. Once the content of a given equalization register has been established, the bits in the next register may be tested. Referring to Figure 36A, for example, coefficient C1 may be established first, then coefficient C2, and so forth.

Coefficients for cross-talk equalization may also be determined using the techniques described in reference to Figures 24 and 29-31. However, rather than measuring margins that
25 result from transmission of a given temporal bit pattern, margins are determined based on spatial bit patterns (e.g., different patterns of bits that are transmitted on nearby channels of the bus at the same time, rather than in succession on a single channel). By toggling each of the bit positions in the pattern, spatial coefficients may be determined and installed in the cross-talk equalization registers for the transmitter under test. Also, each bit of each register may
30 be successively determined by comparing margins measured when the bit is set with margins measured when the bit is reset.

Several exemplary techniques have been presented by which timing offsets and voltage offsets and equalization offsets may be determined during the calibration phase of system operation. There are, however, several issues which should be considered when designing reliable and efficient calibration procedures. Definition of an appropriate calibration data sequence is one such issue.

Multiple calibration sequences are possible, but there are few which are optimal. A first preferred sequence consists of very simple 0-to-1 and 1-to-0 transitions at a data rate (frequency) much lower than the normal data rate of the channel during the bus system operation phase. A data rate with a period is larger than the time memory of the channel, e.g., twice the bus electrical length, will usually be adequate. Since the clock and data receivers functioning as phase receivers in the foregoing embodiments are run at normal frequency during the calibration phase, but the data transfer rate is significantly reduced, any timing skews that arise as a function of the data rate are eliminated. In theory, the low frequency data may be considered the mean of the distribution of offsets in a system having frequency dependent offsets. The various offset registers, or rather the offset values stored therein, are determined using this low frequency data and timing, and voltage skews are minimized accordingly.

This approach works because the channel (data bus) transferring data between the master and slaves reacts differently at different data rates. That is, data at different transfer frequencies results in different offsets which are created by resonances and discontinuities at that frequency. Hypothetically, the center of the distribution for such offsets is actually more or less at the same location as the transitions of very low frequency data, such data can be constructed by large data blocks having a single data transition. Such very low frequency data does not excite harmonics the way higher frequency data can, and the single data transition may be readily discerned within the calibration process. Thus, by phase detecting the very low frequency data in receivers running at much higher clock rates, the timing and voltage offsets may be accurately determined.

A second preferred calibration sequence consists of a spectrum of calibration data which starts at a very low frequency and slowly increases until the fundamental is reached. No data frequency is favored over another in this approach, so each frequency is given the same number of data transitions, and thus phase detector evaluations before the frequency is

changed.

In a third preferred calibration sequence, the master observes the valid data window width using the scanning approach explained above, and determines if the communications channel will reliably run at the given frequency. If the master determines that the valid data window is not adequate, it reduces the operating frequency and re-establishes the valid data window width at the new frequency. Since the master's offset registers are calibrated in degrees for most of the foregoing embodiments, the percentage of valid bit-time required for reliable communication can be stored once for all operating frequencies and the final operating frequency need not be an integer multiple of the initial operating frequency.

Preeminent among calibration issues is the fact that data transfers, and in particular control data transfers, between the master and slaves is inherently suspect before completion of the timing and voltage calibration procedures. Figure 38 shows the exemplary bus system of Figure 5 in some different detail. The communication channel between master and slaves, as further illustrated, typically includes a control bus, and a serial data link, in addition to the data bus and external clock signal(s).

As noted, many contemporary bus systems communicate data between the master and slaves in packets. This is particularly true where the bus system comprises a memory system. Thus, the problem of communicating reliable control data from the master to a slave is often compounded by the packet nature of the communicated control data. In yet another aspect, the present invention addresses this problem.

Figure 38 shows the basic configuration of a packet protocol based memory system. In normal operation, the master sends control data over "n" control lines to one or more slave devices. The slaves decode the command indicated by the control data, and perform the requested operation, such as a read or write operation. During a write operation data is transferred from the master to the slave via the data bus and during a read operation data is returned from a slave to the master via the data bus. The control and data packets are sent synchronously relative to the external reference clock, e.g., CTM and CFM. Since in many high performance applications data packets are transferred on both the rising and falling edges of clock signal, the data packets can be viewed as being "even" or "odd" depending on their relationship to the external (EXT.) clock, as illustrated in Figure 39. The system shown in Figure 38 also includes a slow speed serial link typically used during system initialization

to convey device identification.

Many of the timing adjustment circuits explained above and resident in a slave can be functionally summarized by the diagram in Figure 40. An adjusted internal clock, CLKINT (ADJUSTED), is developed and applied to a slave data receiver or transmitter 400. The
5 adjusted internal clock has been derived from an internal clock (CLKINT) typically generated by a clock recovery circuit 401 on the slave receiving the external clock as an input. The internal clock is adjusted by an delay adjustment circuit 402 providing a delay between $-\tau_D$ and $+\tau_D$ in relation to an adjustment value stored in an offset register 403. Within this generalized approach to timing offset compensation, the master will vary the adjustment
10 offset value in the offset register of the slave while performing a sequence of data writes and reads until an optimal offset value is determined which provides the best overall system margin.

Unfortunately, before the receiver and transmitter timing is calibrated to a master clock signal (EXT.CLK), the read and write command packets sent via the control bus may
15 not be received correctly. Unreliable control makes calibration extremely difficult.

To overcome this difficulty the slow speed serial link might be used to send commands to an un-calibrated slave device. However, this solution presents several problems. First, the serial port is very slow. As a result, the calibration process becomes unwieldy and takes an inordinate amount of time. Second, the slave device is forced to
20 multiplex the slow speed read/write commands with normal control and data transfers. This ability requires significant additional control logic. Such additional hardware may delay certain critical paths during normal slave device operation.

Another approach to overcoming the unreliable nature of control packet transfer to un-calibrated slave devices requires that the control command packet be transmitted at half its
25 normal rate. Such a scheme is illustrated in Figure 41. By running at half the normal rate and delaying control data by one quarter cycle, bits on the control bus lines have twice the ordinary timing margin. Such expanded timing margin is sufficient to reliably transfer control data even without calibration of the slave device. Transmitting only the even control bits shifted forward by 90° would provide control data having a similarly expanded timing
30 margin.

While generally superior to transmitting control packets via the serial link, the

foregoing technique presents some challenges to the system designer. The slave device must be capable of responding to two different protocols - one for regular operation and the other for calibration. Several exemplary techniques for accomplishing this result are explained below.

5 Assuming as an example that the slave is a memory device, the control packet typically consists of bit fields representing a number of different components including: a Device ID identifying which slave device is being accessed, an Opcode identifying the nature of the operation, an Address identifying a location related to the operation, and a Write Mask selecting a portion of write data to be stored.

10 During calibration of the memory device not all of these fields are required. For example, if the system has a method of enabling/disabling the memory device through the serial link, which is typical, then the Device ID field is not needed during calibration. All memory devices other than the one being calibrated can be readily disabled using the serial link. The Write Mask need not be use during calibration. Further, only a subset of the
15 normal Opcodes are required during calibration, since the memory device need only perform simple read and write commands. Finally, only a portion of the typical Address field is required. The addressable memory requirements of the memory device during calibration are greatly reduced as compared to normal operation. Accordingly, many of the control packet bits may be utilized for other purposes during calibration.

20 Figure 42 compares the format of a normal operation control packet with the format of a calibration mode control packet. The example assumes a four clock cycle transfer period, a five line control bus, and "normal" odd/even transfer on the rising and falling edges of the clock. In the example "D" bits are Device ID bits, "O" bits are Opcode bits, "ST" are framing bits, "M" bits are Write Mask bits, and "A" bits are Address bits.

25 In the calibration mode data packet, required calibration bits are placed in the odd positions. The even positioned bits effectively become "don't care" bits. This arrangement of bits allows the same overall control packet format and protocol to be used during normal and calibration modes of operation.

30 During calibration, the control packet decode logic will receive correct bits for the odd bits and "don't care" bits for even bits. The logic used to decode control data during normal operation requires remarkably little modification to also decode control data during

calibration. As shown in Figure 43, only the single additional gate and control line, combined 420, need be added to the normal logic.

In the example illustrated by Figures 42 and 43, a serial register bit causes all control packets to be processed, regardless of the state of the control packet D[4:0] bits or the device ID register. As long as the serial register bit is set before calibration starts and the system does not perform any masked writes, the control link will operate reliably with the expanded margins described above.

Restrictions on addressable memory space brought about by the foregoing must be considered when a calibration sequence is defined. Furthermore, as Opcode and Address bits are cannibalized using this approach, the control packet format and the corresponding calibration control logic must also be modified. Such tradeoffs are well within ordinary skill in the art. The foregoing examples of the control packet and its associated decode logic are highly specific to a presently preferred embodiment of the bus system. Any reasonable control packet format, definition of bits, and resulting decoding logic might be used to effect dual operation of the memory device, as between normal operation and calibration, with minimal overhead.

The foregoing embodiments of the present invention illustrate various implementations of the timing and/or voltage control circuitry in the slave devices of an exemplary bus system. However, bus system designers may wish to minimize the size, cost, and complexity of the slave devices. Alternatively, bus system designers may provide a very powerful master device. Whatever the motivation for doing so, the timing and/or voltage control circuits previously described as being resident in individual slave devices may be implemented in the master.

A master incorporating such circuits may generally implement voltage/timing adjustments in one of two ways: a mean control approach or an individual control approach. In the mean control approach, optimizing voltage/timing offsets are calibrated for each slave device during calibration. Once a field of offset values have been calculated, a mean offset value is determined in the master. This mean offset value is stored in a register on the master and used to adjust the read/write timing or the read/write voltage for data being communicated between the master and all slave devices.

In the individual slave device control approach, a separate timing/voltage offset value

is stored in the master for each slave to produce a field of timing/voltage offset values. As described above, an appropriate offset value may be determined for each slave during calibration. Once determined, the offset value is specifically applied to read/write operations involving the corresponding slave.

5 Figure 44 illustrates one example in which current control is implemented for each slave device on an individual basis using offset values stored in the master. As is typical in many contemporary bus systems, this example assumes that each slave device (12a-12n) is identified within the bus system by a unique device ID. Thus, a "request" to access (read/write) data in one slave will include a device ID indicator. The example shows a device
10 ID map circuit 430 receiving a request and extracting a device ID signal from it. The device ID signal is applied to a selector circuit 431, such as a MUX, which also receives a plurality of offset values. Current control registers 432 (CCTLa, CCTLb . . . CCTLn) each contain an offset value for a corresponding slave device (12a, 12b, . . . 12n). A broadcast control register CCTL (BCT) 433 is also provided. The offset value stored in broadcast control register is
15 used by the master when communicating data to all slave devices. This offset value may be the mean control value mentioned above.

 However, in normal operating mode, the device ID extracted from a slave access request is used to select a corresponding current control offset value for the accessed slave device. The selected current control offset value is then applied to a drive circuit 434 which
20 adjusts the current of write signals (control or data) being sent to the slave device. The example shows a single signal line, but one or more drive circuits may adjust the output current on a number of data bus signal lines.

 From this specific example, one of ordinary skill in the art may see that a very similar approach may be taken to implement read signal voltage adjustments in the master. Further,
25 read/write timing adjustments may also be made on the basis of a mean timing offset value or a field of timing offset values stored in the master. Timing control adjustment may be made in relation to a particular offset value by adjusting the master read/write clock signal, or by communicating an slave devices specific internal read/write signal via a signal line.

What is claimed is:

1 1. A bus system comprising a master and a slave connected via a data bus, the master
2 and the slave each receiving a master clock signal, and the slave further comprising:
3 a write offset register storing a write offset value;
4 a receiver receiving data from the data bus in accordance with an internal write clock
5 signal;
6 a receive locked loop circuit generating the internal write clock signal in relation to
7 the master clock signal, wherein the internal write clock varies from the master clock signal
8 in accordance with the write offset value.

1 2. The bus system of claim 1, wherein the slave further comprises:
2 a read offset register storing a read offset value;
3 a transmitter transmitting data onto the data bus in accordance with an internal read
4 clock signal;
5 a transmit locked loop circuit generating the internal read clock signal in relation to
6 the master clock signal, wherein the internal read clock varies from the master clock signal in
7 accordance with the read offset value.

1 3. The bus system of claim 2, wherein the receive locked loop and the transmit locked
2 loop circuits are delay locked loop circuits.

1 4. A bus system comprising:

2 a master and a plurality of N slave devices connected via a data bus, wherein the
3 master communicates data to and from each one of the plurality of N slave devices during a
4 valid data period T;

5 wherein the master and each one of the plurality of N slave devices receives a master
6 clock signal, and

7 wherein each one of the plurality of N slave devices comprises:

8 a receiver receiving data from the data bus upon transition of an internal write clock
9 signal;

10 a transmitter transmitting data onto the data bus upon transition of an internal read
11 clock signal; and

12 a timing adjustment circuit receiving the master clock signal and adjusting the
13 internal write clock signal and the internal read clock signal, such that the transition of the
14 internal write clock signal and the transition of the internal read clock signal occur at the
15 center of period T.

1 5. The bus system of claim 4, wherein the timing adjustment circuit comprises:

2 a clocking circuit receiving the master clock signal and generating the internal write
3 clock signal and the internal read clock signal in relation to the master clock signal;

4 a write offset register connected to the clocking circuit and storing a write offset
5 value, wherein the internal write clock signal is generated in accordance with write offset
6 value; and

7 a read offset register connected to the clocking circuit storing a read offset value,
8 wherein the internal read clock signal is generated in accordance with read offset value.

1 6. The bus system of claim 5, wherein the clocking circuit is a delay locked loop
2 circuit.

1 7. The bus system of claim 5, wherein the master comprises:

2 circuitry capable of individually determining an appropriate read offset value and
3 write offset value for each one of the plurality of N slave devices.

1 8. A bus system comprising:
2 a master and a slave device connected via a data bus, wherein the master
3 communicates data to the slave device during a valid data period T;
4 wherein the slave devices comprises:
5 a receiver receiving data from the data bus upon transition of an internal write clock
6 signal; and,
7 a timing adjustment circuit receiving the master clock signal and adjusting the
8 internal write clock signal such that the transition of the internal write clock signal occur at
9 approximately the center of period T.

1 9. The bus system of claim 8, wherein the timing adjustment circuit further
2 comprises:
3 a delay locked loop (DLL) circuit receiving the master clock signal and generating
4 one or more reference signals;
5 a vector circuit receiving the one or more reference signals and generating a plurality
6 of output signals having different phases;
7 a match delay circuit receiving at least one of the vector circuit output signals and
8 generating the internal write clock signal;
9 a write offset register storing a write offset value;
10 a phase mixer receiving the plurality of output signals from the vector circuit and
11 receiving a signal indicative of the write offset value, and generating a write offset feedback
12 signal applied to the DLL circuit to adjust the internal write clock signal in accordance with
13 the write offset value.

1 10. The bus system of claim 8, wherein the timing adjustment circuit further
2 comprises:

3 a write offset register storing a write offset value;
4 a clocking circuit comprising a receive phase detector circuit receiving the master
5 clock signal, receiving a write offset feedback signal, and generating the internal write clock
6 signal in response to the master clock signal and the write offset feedback signal;
7 a variable delay circuit receiving the internal write clock signal from the clocking
8 circuit and adjusting its delay in accordance with the write offset value to form the write
9 offset feedback signal.

1 11. The bus system of claim 10, wherein the clocking circuit is a delay locked loop,
2 and the variable delay circuit further comprises:

3 a binary weighted chain of inverters variably switched to and from the path of the
4 write offset feedback signal in accordance with the write offset value.

1 12. The bus system of claim 8, wherein the timing adjustment circuit further
2 comprises:

3 a write offset register storing a write offset value;
4 a clocking circuit comprising a receive phase detector circuit receiving a master clock
5 signal, a first write offset feedback signal and a second write offset feedback signal, and
6 generating the internal write clock signal in response to master clock signal and the write
7 offset feedback signal;

8 a first binary weighted chain of current sources controlled by at least a portion of the
9 write offset value and generating the first write offset feedback signal; and

10 a second binary weighted chain of current sources controlled by at least a portion of
11 the write offset value and generating the second write offset feedback signal.

13. The bus system of claim 12, wherein the clocking circuit is a delay locked loop.

1 14. The bus system of claim 8, wherein the timing adjustment circuit further
2 comprises:
3 a write offset register storing a write offset value;
4 a first phase detector receiving a master clock signal and a write offset feedback signal
5 and generating a control signal;
6 a reference loop receiving the master clock signal, generating a plurality of reference
7 signals having different phases, and generating a reference control voltage;
8 an interpolator generating the internal write clock signal in accordance with the
9 control signal received from the first phase detector and the plurality of reference signals
10 received from the reference loop;
11 an internal write clock signal buffer receiving the internal write clock signal from the
12 interpolator; and
13 a write offset feedback signal buffer coupled to the write offset register, receiving the
14 internal write clock signal from the interpolator, and adjusting the delay of the internal write
15 clock signal in accordance with the write offset value to form the write offset feedback signal.

1 15. The bus system of claim 14, wherein the reference loop further comprises:
2 a series of buffers receiving the master clock signal and producing the plurality of
3 reference signals;
4 a second phase detector receiving first and second ones of the plurality of reference
5 signals and generating a pump control signal in response thereto;
6 a charge pump receiving the pump control signal and generating the reference control
7 voltage in accordance with the pump control signal.

1 16. The bus system of claim 8, wherein the timing adjustment circuit further
2 comprises:

3 a write offset register storing a write offset value;

4 a clocking circuit providing reference vectors to a main interpolator and an offset
5 interpolator;

6 wherein the main interpolator generates a write offset feedback signal and the offset
7 interpolator generates the internal write clock signal;

8 a phase detector receiving the write offset feedback signal and the master clock signal
9 and generating an output signal;

10 a main counter receiving the output signal and generating a main counter signal
11 applied to the main interpolator;

12 an adder circuit receiving the main counter signal and a signal indicative of the write
13 offset value and generating an up/down signal;

14 an offset counter receiving the up/down signal and generating an offset counter signal
15 applied to the offset interpolator.

1 17. A bus system comprising a master and a slave connect via a data bus, the slave
2 receiving data from the master via the data bus in a first voltage state and a second voltage
3 state, wherein the difference between the first voltage state and the second voltage state
4 defines a voltage swing, the slave comprising:

5 a write voltage offset circuit storing a write voltage offset value;

6 a write voltage compensating circuit receiving a reference voltage and a signal
7 indicative of the write offset value, and adjusting the voltage swing of the received data such
8 that the first voltage state and the second voltage state are proximately centered about the
9 reference voltage.

1 18. A bus system comprising a master and a slave connect via a data bus, the slave
2 transmitting data to the master via the data bus in a first voltage state and a second voltage
3 state, wherein the difference between the first voltage state and the second voltage state
4 defines a voltage swing, the slave comprising:

5 a read offset circuit storing a read offset value;

6 a read compensating circuit receiving data to be transmitted to the master and a signal
7 indicative of the read offset value, and adjusting the voltage swing of the transmitted data
8 such that the first voltage state and the second voltage state are proximately centered about a
9 reference voltage.

1 19. The bus system of claim 18, wherein the read compensating circuit receives data
2 to be transmitted to the master and the signal indicative of the read offset value, and adjusts
3 the current of the driver placing the data onto the data bus such that the first voltage state and
4 the second voltage state are proximately centered about a reference voltage.

5 a receiver receiving data from the data bus in accordance with an internal write clock
6 signal;

7 a receive locked loop circuit generating the internal write clock signal in relation to
8 the master clock signal, wherein the internal write clock varies from the master clock signal
9 in accordance with the write offset value.

1 20. A bus system comprising a master and a slave connected via a data bus,
2 the slave comprising:
3 a first clocking circuit receiving a master clock signal;
4 a write offset register storing a write offset value connected to the first clocking
5 circuit;
6 a read offset register storing a read offset value connected to the first clocking circuit;
7 wherein the first clocking circuit generates an internal write clock signal varying in
8 relation to the master clock signal in accordance with the write offset value, and generates an
9 internal read clock signal varying in relation to the master clock signal in accordance with the
10 read offset value;
11 the master comprising:
12 a second clocking circuit capable of generating a normal clock and a calibration
13 shifted clock being shifted 90° from the normal output clock.

1 21. The bus system of claim 20, wherein the first and second clocking circuits are
2 delay locked loop circuits or phase locked loop circuits.

1 22. A method of adjusting read timing and write timing in a slave device receiving
2 data from a master and transmitting data to the master, the method comprising:
3 receiving a master clock signal in the slave device;
4 storing a write offset value and a read offset value;
5 generating an internal read clock signal varying from the master clock signal in
6 accordance with the read offset value, and reading data into the slave device synchronous
7 with the internal read clock signal;
8 generating an internal write clock signal varying from the master clock signal in
9 accordance with the write offset value, and writing data to the master synchronous with the
10 internal write clock signal.

1 23. The method of claim 22, wherein the write offset value is stored in a write offset
2 register in the slave device and wherein the read offset value is stored in a read offset register
3 in the slave device.

1 24. A method of adjusting write timing in a bus system comprising a master
2 connected to a slave device via a data bus, the method comprising:
3 storing a write offset value associated with the slave device;
4 receiving a master clock signal in the slave device;
5 generating an internal write clock signal in relation to the master the clock signal and
6 the write offset value;
7 receiving data from the master synchronous with the internal write clock signal.

1 25. The method of claim 24, wherein the step of generating an internal write clock
2 signal further comprises:
3 generating a plurality of reference signals in a clocking circuit;
4 generating a set of vector signals having different phases using at least one of the
5 plurality of reference signals;
6 outputting one signal from the set of vector signals through a matched delay as the
7 internal write clock signal;
8 generating a write offset feedback signal to the clocking circuit in relation to a signal
9 indicative of the write offset value and the set of vector signals.

1 26. The method of claim 25, wherein the clocking circuit comprises a delay locked
2 loop;

1 27. The method of claim 26, wherein the step of generating a write offset feedback
2 signal is performed in a phase mixer receiving the signal indicative of the write offset value
3 and the set of vector signals.

1 28. The method of claim 24, wherein the step of generating an internal write clock
2 signal further comprises:
3 receiving a master clock signal and a write offset feedback signal in a clocking circuit
4 phase detector;
5 generating the internal write clock signal in the clocking circuit;
6 generating the write offset feedback signal in accordance with the write offset value.

1 29. The method of claim 28, wherein the step of generating the write offset feedback
2 signal further comprises:
3 applying the internal write clock signal to a variable delay circuit; and,
4 adjusting the delay of the internal write clock signal in the variable delay circuit in
5 accordance with the write offset value to generate the write offset feedback signal.

1 30. The method of claim 24, wherein the step of generating an internal write clock
2 signal further comprises:
3 applying at least a portion of the write offset value to a first binary weighted chain of
4 current sources and a second binary weighted chain of current sources to generate
5 respectively first and second write offset feedback signal;
6 applying the first and second write offset feedback signals to a clocking circuit phase
7 detector circuit to generate the internal write clock signal.

1 31. The method of claim 24, wherein the step of generating an internal write clock
2 signal further comprises:

3 receiving a master clock signal and a write offset feedback signal in a phase detector
4 and generating a control signal;

5 generating a plurality of reference signals having different phases in a reference loop
6 receiving the master clock signal;

7 generating a reference control voltage in the reference loop;

8 generating the internal write clock signal in an interpolator in accordance with the
9 control signal and the plurality of reference signals;

10 applying the internal write clock signal to an internal write clock signal buffer and to
11 a write offset feedback signal buffer; and

12 adjusting the delay of the internal write clock signal in the write offset feedback signal
13 buffer in accordance with the write offset value to form the write offset feedback signal.

1 32. The method of claim 24, wherein the step of generating an internal write clock
2 signal further comprises:

3 applying phased reference vectors from a delay locked loop circuit to parallel first and
4 second interpolators, the first interpolator generating the internal write clock signal and the
5 second interpolator functioning in a feedback loop providing a write offset feedback signal to
6 the first interpolator;

7 adjusted the write offset feedback signal in the feedback loop using the write offset
8 value.

1 33. The method of claim 24, wherein the step of generating an internal write clock
2 signal further comprises:

3 applying a plurality of reference vectors received from a clocking circuit to a main
4 interpolator and a offset interpolator;

5 generates a write offset feedback signal in the main interpolator;

6 generating the internal write clock signal in the offset interpolator;

7 applying the write offset feedback signal and the master clock signal to a phase
8 detector and generating an output signal;

9 applying the output signal to a main counter and generating a main counter signal;

10 applying the main counter signal to the main interpolator;

11 applying the main counter signal and a signal indicative of the write offset value to an
12 adder circuit and generating an up/down signal;

13 applying the up/down signal to an offset counter and generating an offset counter
14 signal;

15 applied the offset counter signal to the offset interpolator.

1 34. A method of adjusting a voltage swing for data in a bus system comprising a
2 master connected to a plurality of slaves via a data bus, the method comprising:

3 for each slave in the plurality of slaves, individually,

4 storing an input voltage offset value in a register on the slave;

5 receiving data at the slave from the master via the data bus;

6 adjusting the voltage swing of the received data in accordance with the input voltage
7 offset value.

1 35. A method of adjusting a voltage swing for data in a bus system comprising a
2 master connected to a plurality of slaves via a data bus, the method comprising:

3 for each slave in the plurality of slaves, individually,

4 storing a driver current offset value in a register on the slave;

5 adjusting output current for a data driver in the slave in accordance with the driver
6 current offset value.

1 36. A method of adjusting a data voltage levels in a bus system comprising a master
2 connected to a plurality of slave devices via a data bus, the method comprising:
3 individually determining for each slave device in the plurality of slave devices at least
4 one voltage offset;
5 within each slave device, applying the at least one individually determined voltage
6 offset to the data voltage levels data received from the master via the data bus.

1 37. The method of claim 36, wherein the at least one voltage offset for each slave
2 device is determined in relation to a reference voltage.

1 38. The method of claim 37, wherein the reference voltage is externally generated
2 from the slave device.

1 39. The method of claim 36, wherein the step of individually determining for each
2 slave device in the plurality of slave devices at least one voltage offset, further comprises:
3 for each slave device, scanning the data voltage levels for data received from the
4 master to determine upper and lower failure points and determining the at least one voltage
5 offset in relation to the upper and lower failure points.

1 40. A method of determining a compensating voltage offset applied to data received
2 by a slave device from a master via a data bus in a bus system in which a reference voltage is
3 normally communicated from the master to the slave via a reference voltage signal line, the
4 method comprising:
5 communicating a test voltage signal from the master to the slave via one or more
6 signal lines of the data bus;
7 applying the test voltage signal to the reference voltage signal line;
8 comparing in the slave device the level of the test voltage signal on the one or more
9 signal lines of the data bus with the level of test voltage signal on the reference voltage signal
10 line;
11 determining the compensating voltage offset in relation to the comparison of test
12 voltage signal levels.

1 41. A method of determining a compensating drive current offset for a slave device
2 transmitting data to a master via a data bus, the method comprising:
3 driving data onto the data bus at the slave device;
4 receiving the data at the master in a comparator circuit and comparing the voltage
5 level of the data to a reference voltage;
6 generating an up/down signal on the basis of the comparison between the data voltage
7 level and the reference voltage;
8 communicating the up/down signal from the master to the slave device;
9 adjusting a value in current control register in relation to the up/down signal, wherein
10 the value in the current control register defines the drive current offset for the slave device.

1 42. The method of claim 41, wherein the step of driving data onto the data bus further
2 comprises:
3 driving a high data value on a first signal line of the data bus and driving a low data
4 value on a second signal line of the data bus; and,
5 wherein the comparator circuit further comprises:
6 a precision resistor divider switched between the first and second signal lines.

1 43. A method of determining a timing adjustment offset for a slave device receiving
2 data from a master via a data bus, the method comprising:
3 shifting the transmit clock in the master by 90°;
4 outputting a calibration data sequence from the master;
5 adjusting an internal write clock in the slave device to determine the center point for a
6 data transition period defined by the shifted master transmit clock; and
7 determining the timing adjustment offset in relation to the determination of the center
8 point for the data transition period.

1 44. The method of claim 43, wherein the internal write clock is adjusted by
2 incrementing or decrementing a value stored in an write offset register in the slave device.

1 45. The method of claim 44, wherein the step of adjusting an internal write clock in
2 the slave device to determine the center point for a data transition period defined by the
3 shifted master transmit clock, further comprises:

- 4 (a) adjusting the internal write clock and reading the data received from the master;
5 (b) decrementing the value of the write offset register when a high data value is read
6 or incrementing the value of the offset register when a low data value is read;
7 (c) continuing steps (a) and (b) until such time as the value of the write offset register
8 toggles with each successive adjustment of the internal write clock.

1 46. The method of claim 43, wherein the calibration data sequence comprises a
2 relatively large data block having a single data transition between a high data value and a low
3 data value.

1 47. A method of determining a timing adjustment offset for a slave device
2 transmitting data to a master via a data bus, the method comprising:
3 shifting the receive clock in the master by 90°;
4 outputting a calibration data sequence from the slave device;
5 using a receiver in the master as a phase detector, determining the center point for a
6 data transition period defined by an internal read clock in the slave device; and
7 determining the timing adjustment offset for the internal read clock in relation to the
8 determination of the center point for the data transition period.

1 48. The method of claim 47, wherein the internal read clock is adjusted by
2 incrementing or decrementing a value stored in an read offset register in the slave device.

1 49. A method of determining a timing adjustment offset for a slave device internal
2 write clock in relation to a data eye defined by a master transmit clock, the method
3 comprising:

4 scanning a sample clock signal across the breadth of the data eye to determine a
5 leading and a lagging edge of the data eye;

6 defining a timing adjustment offset for the slave device internal write clock in relation
7 to the determination of the leading and lagging edges of the data eye.

1 50. The method of claim 49, wherein the step of scanning of the sample clock is
2 performed by at least one offset interpolator.

1 51. The method of claim 50, wherein the step of scanning the sample clock further
2 comprises:

3 (a) reading a specific offset value from a range of offset values stored in a register;
4 (b) applying the specific offset value to the at least one offset interpolator;
5 (c) repeating steps (a) and (b) until the leading and lagging edges of the data eye have
6 been determined.

1 52. A method of communicating control information in a bus system comprising a
2 master connected to a slave via a bus, the method comprising:

3 during normal operation of the bus system following calibration, communicating
4 control information from the master to the slave in normal packets having a first period;

5 during calibration of the bus system, communicating control information from the
6 master to the slave in calibration packets having a second period greater than the first period.

1 53. The method of claim 52, wherein the normal packets are arranged as even packets
2 sent from the master to the slave on the rising edge of a master clock and odd packets sent
3 from the master to the slave on the falling edge of the master clock.

1 54. The method of claim 53, wherein the second period is twice as long as the first
2 period.

1 55. The method of claim 54, wherein a normal packet is sent from the master to the
2 slave in alternating even and odd packets over a number of master clock cycles.

1 56. The method of claim 55, wherein the calibration packet is sent from the master to
2 the slave in even and odd packets over the number of master clock cycles, where control
3 information contained in the even packets is duplicated in the odd packets.

1 57. A method of communicating control information in a bus system comprising a
2 master connected to a slave via a bus, the method comprising:
3 during normal operation of the bus system following calibration, communicating
4 control information from the master to the slave in normal packets having a first period and
5 having a normal packet format;
6 during calibration of the bus system, communicating control information from the
7 master to the slave in calibration packets having a second period twice the first period and
8 having a calibration packet format.

1 58. The method of claim 57, wherein the calibration packet format allows fewer
2 opcodes definitions than the normal packet format.

1 59. The method of claim 57, wherein the calibration packet format contains fewer
2 write mask bits than the normal packet format.

1 60. The method of claim 57, wherein the calibration packet format contains fewer
2 address bits than the normal packet format.

1 61. The method of claim 57, wherein the calibration packets are communicated via a
2 slow speed serial link between the master and slave device.

1 62. A bus system comprising a master and a plurality of slaves connected via a data
2 bus, the master comprising:
3 means for determining a plurality of offset values, each one of the plurality of offset
4 values corresponding to one of the plurality of slaves;
5 at least one circuit storing the plurality of offset values; and,
6 a selection circuit selecting one of the plurality of offset values.

1 63. The bus system of claim 62, wherein each one of the plurality of slaves is
2 identified within the bus system by a unique device ID, the bus system further comprising:
3 a circuit extracting a device ID from an access request;
4 wherein the selection circuit receives the device ID and selects the one offset value in
5 response thereto.

1 64. The bus system of claim 63, wherein the offset value comprises one selected from
2 a group consisting of:
3 a current control offset adjusting a current level for write signals sent from the master
4 to the slave;
5 a read voltage control offset adjusting a voltage level for read signals sent from the
6 slave to the master;
7 a read timing control offset adjusting a read clock; and,
8 a write timing control offset adjusting a write clock.

1 65. A method of adjusting read/write timing in a bus system comprising a master and
2 a plurality of slaves, the method comprising:
3 determining a timing offset value for each slave in relation to a master clock signal to
4 produce a field of slave timing offset values;
5 determining a mean timing offset value from the field of slave timing offset values;
6 and
7 adjusting read/write timing in the bus system in relation to the mean timing offset
8 value.

1 66. A method of adjusting signal voltage in a bus system comprising a master and a
2 plurality of slaves, the method comprising:
3 determining a voltage offset value for each slave in relation to a reference voltage
4 signal to produce a field of slave voltage offset values;
5 determining a mean voltage offset value from the field of slave voltage offset values;
6 and
7 adjusting read/write signal voltages in the bus system in relation to the mean voltage
8 offset value.

1 67. A method of adjusting signal voltage in a bus system comprising a master and a
2 plurality of slaves, the method comprising:
3 determining a voltage offset value for each slave in relation to a reference voltage
4 signal to produce a field of slave voltage offset values;
5 storing the field of slave voltage offset values in the master; and
6 individually adjusting read/write signal voltages for signals communicated between
7 the master and each one of the plurality of slaves on the basis of a selected one of the field of
8 slave voltage offset values.

1 68. The method of claim 68, wherein one of the field of slave voltage offset values is
2 selected on the basis of a unique slave device ID extracted from an access directed to the
3 slave.

1 69. A method of adjusting write signal timing in a bus system comprising a master
2 and a plurality of slaves, the method comprising:
3 determining a write signal offset value for each slave in relation to a master clock
4 signal to produce a field of slave write signal offset values;
5 storing the field of slave write signal offset values in the master; and
6 individually adjusting write timing for signals communicated from the master to each
7 one of the plurality of slaves on the basis of a selected one of the field of slave write signal
8 timing offset values.

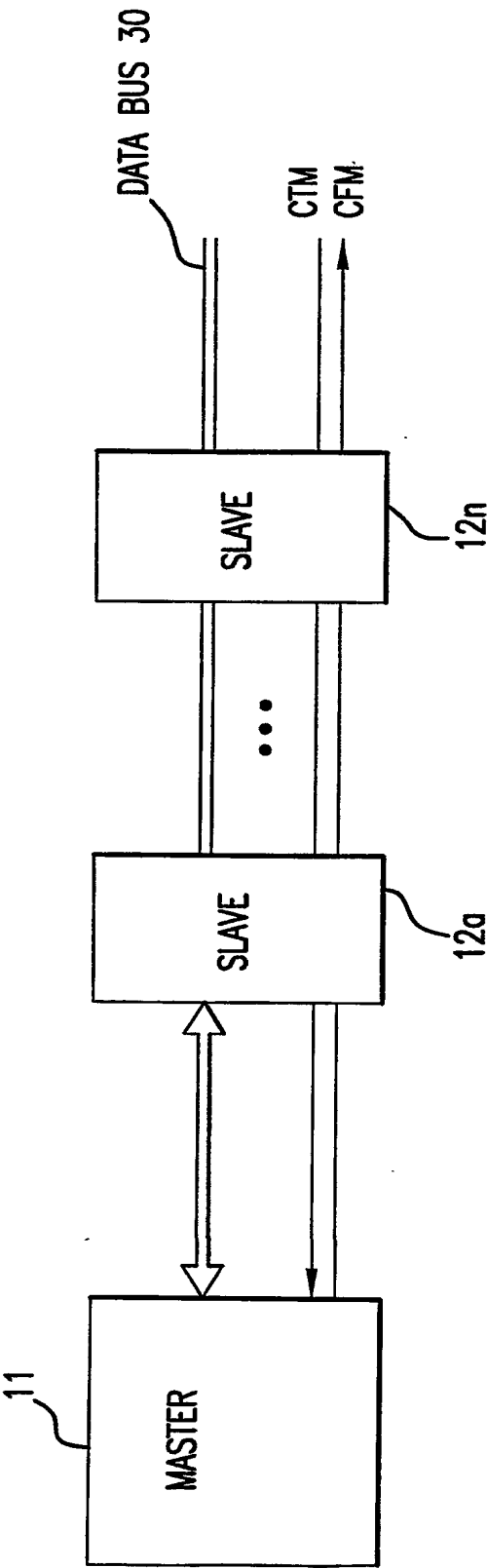


FIG.1

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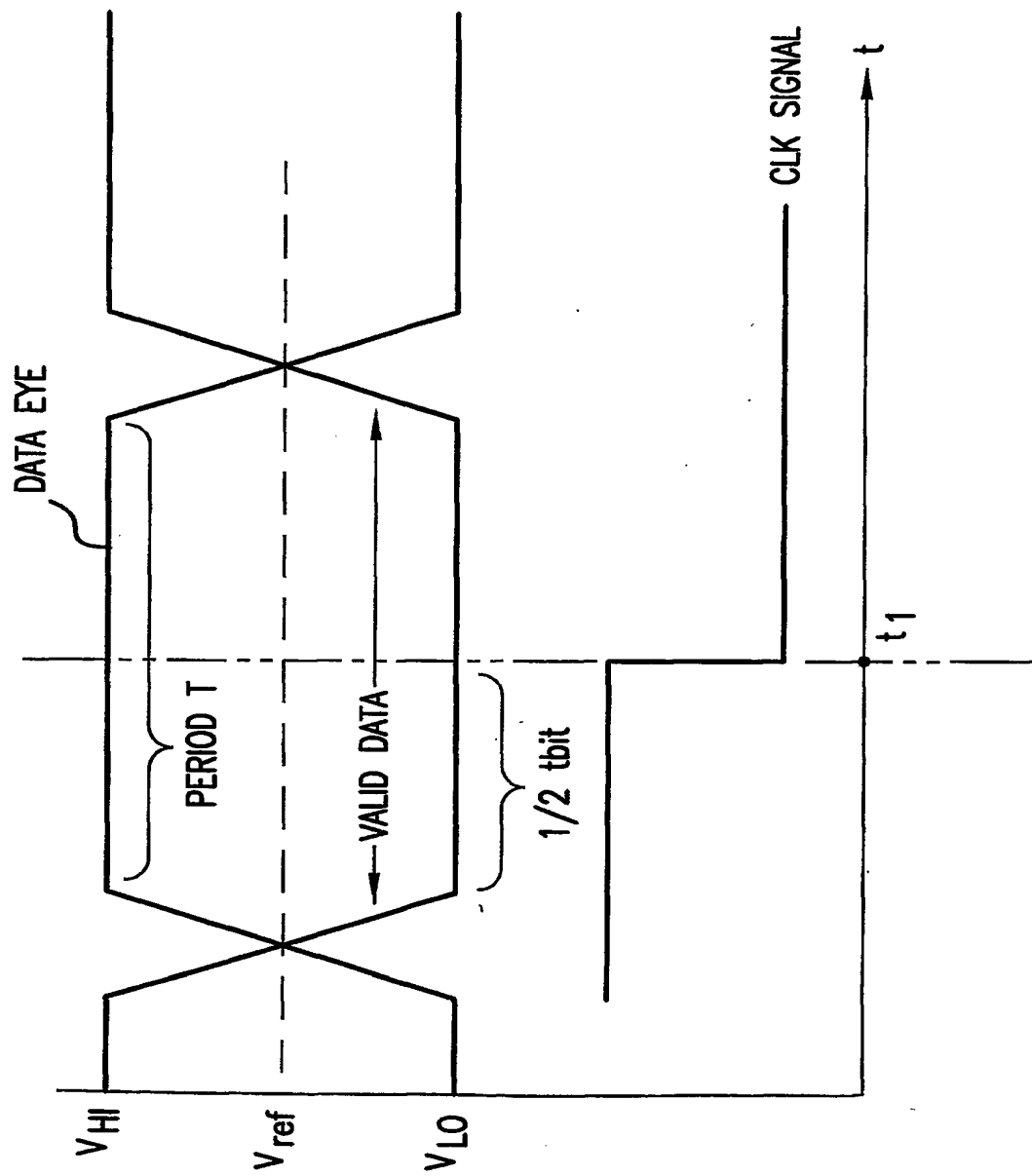


FIG.2

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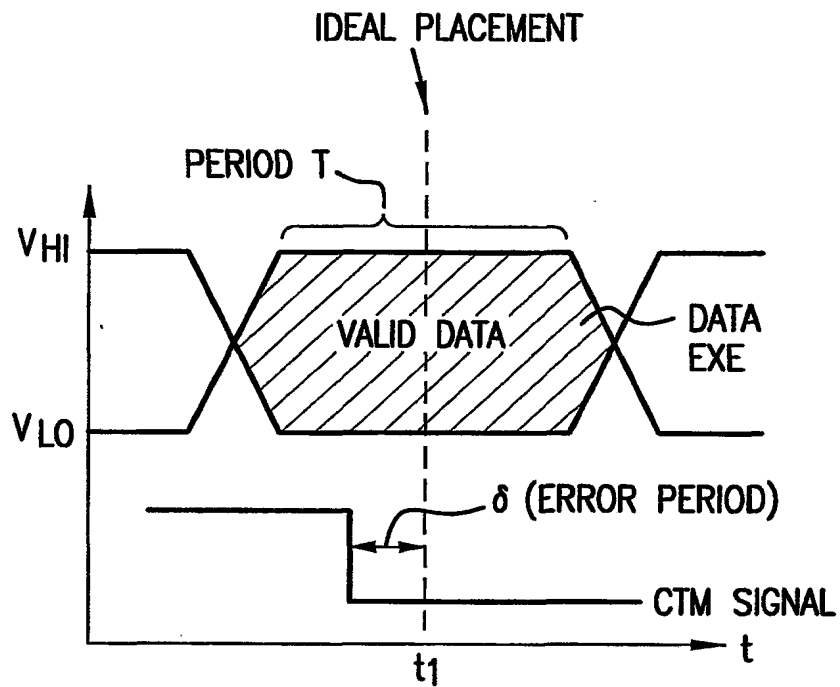


FIG.3A

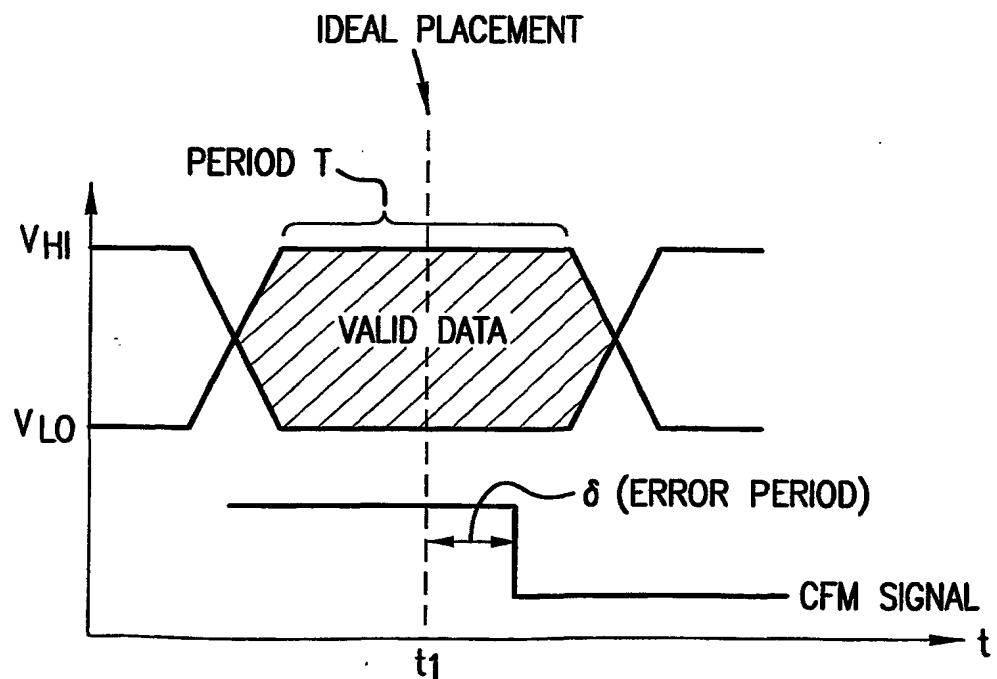


FIG.3B

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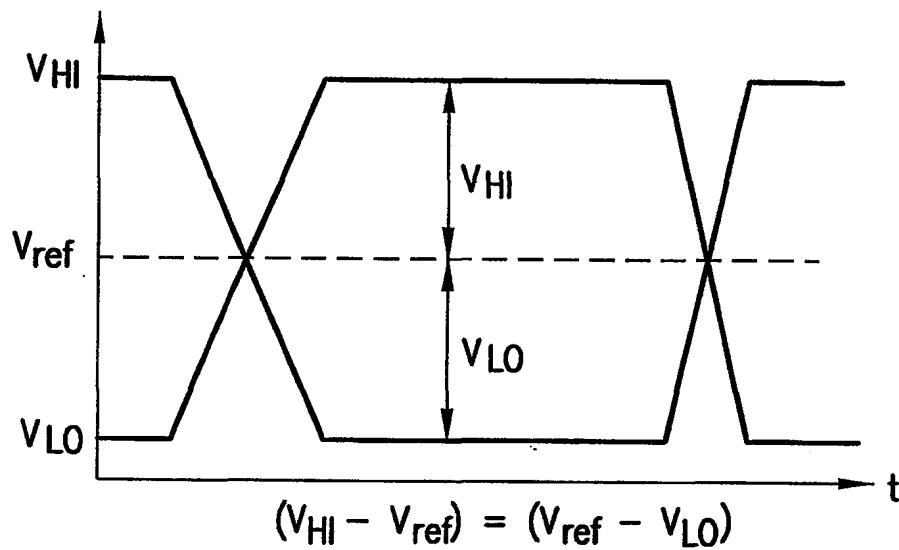


FIG. 4A

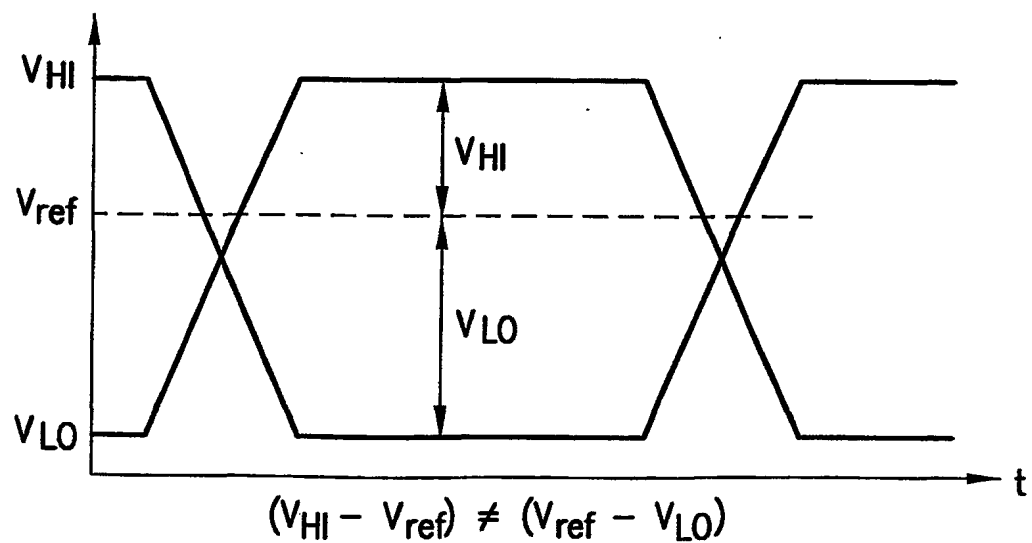


FIG. 4B

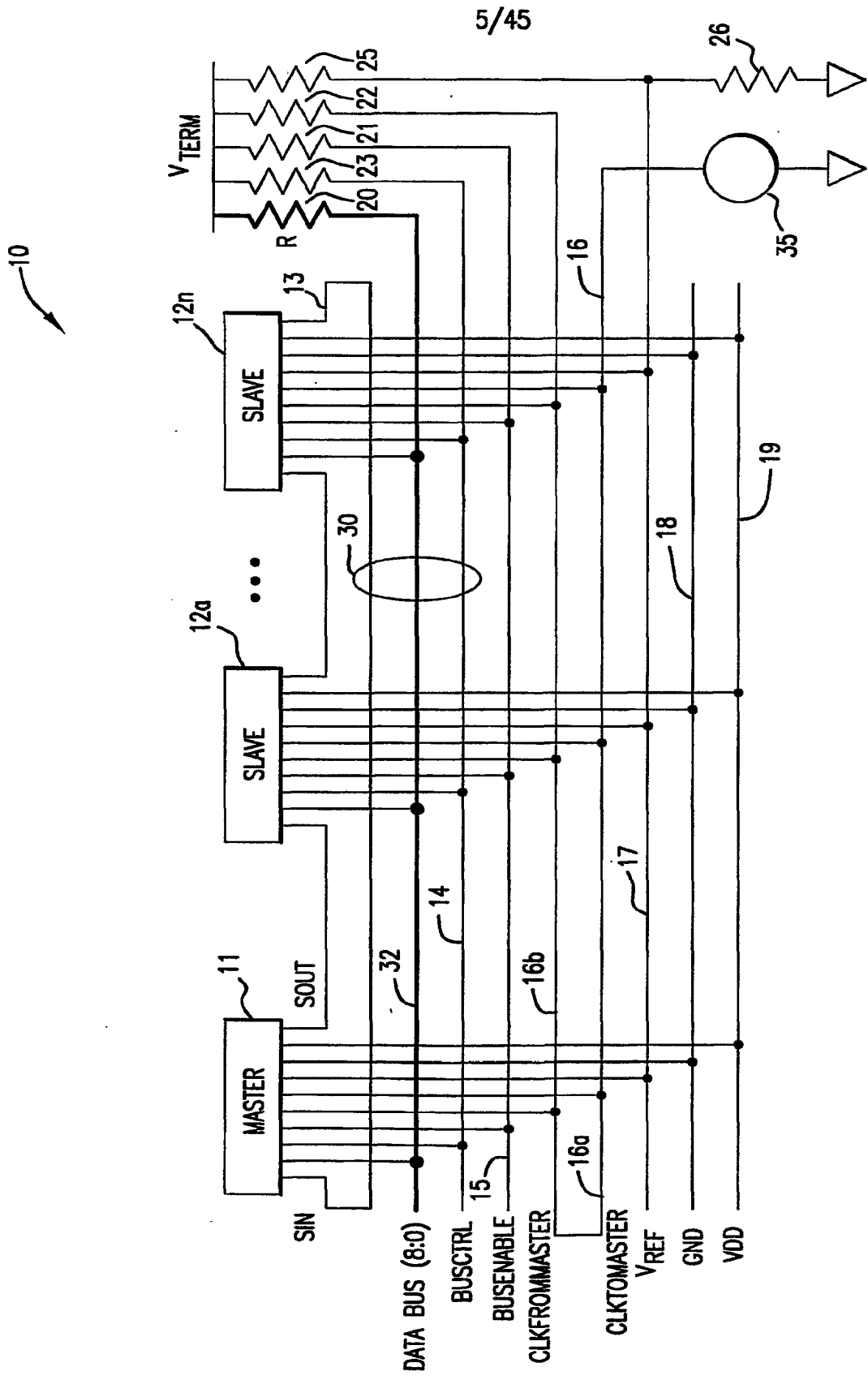


FIG.5

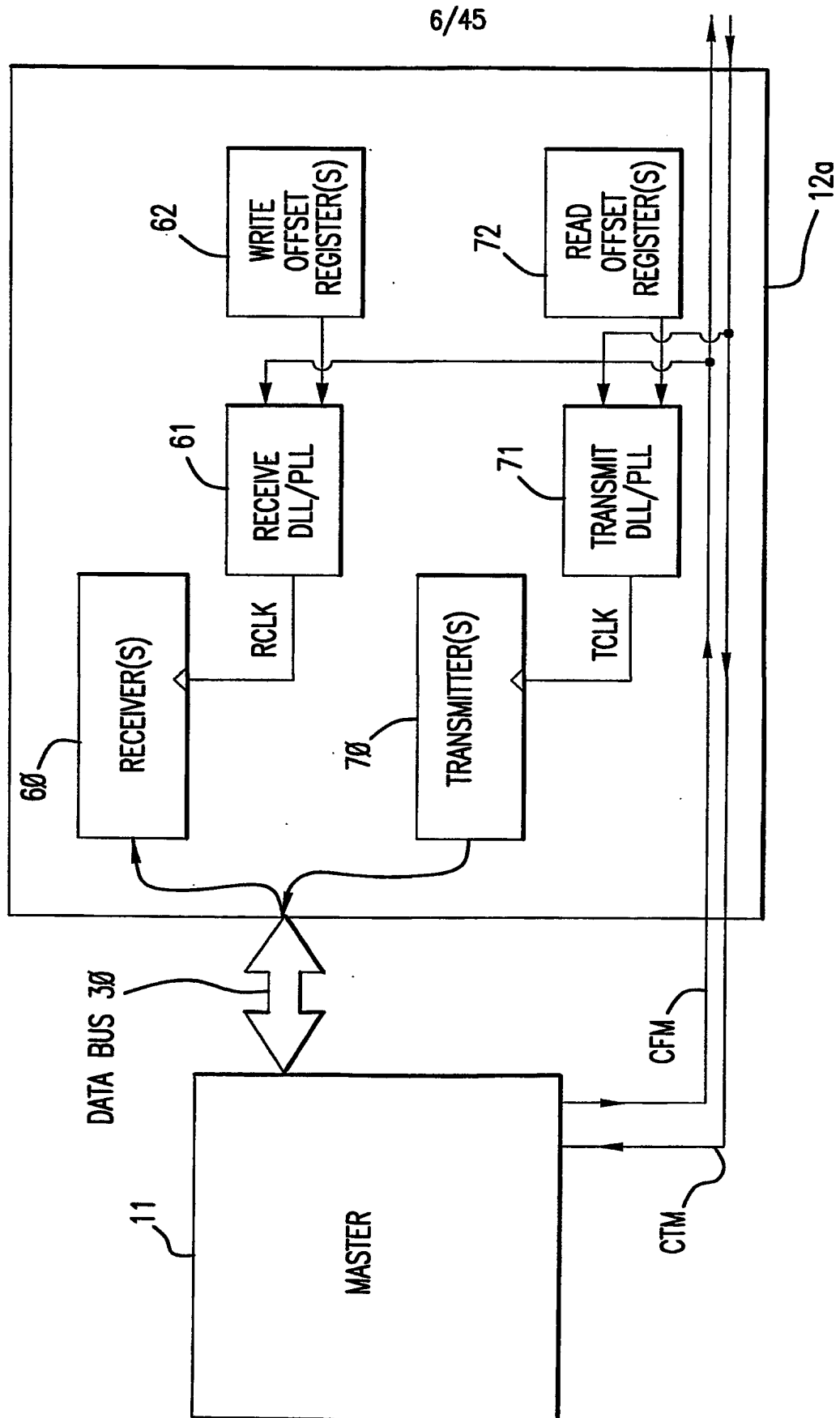


FIG. 6

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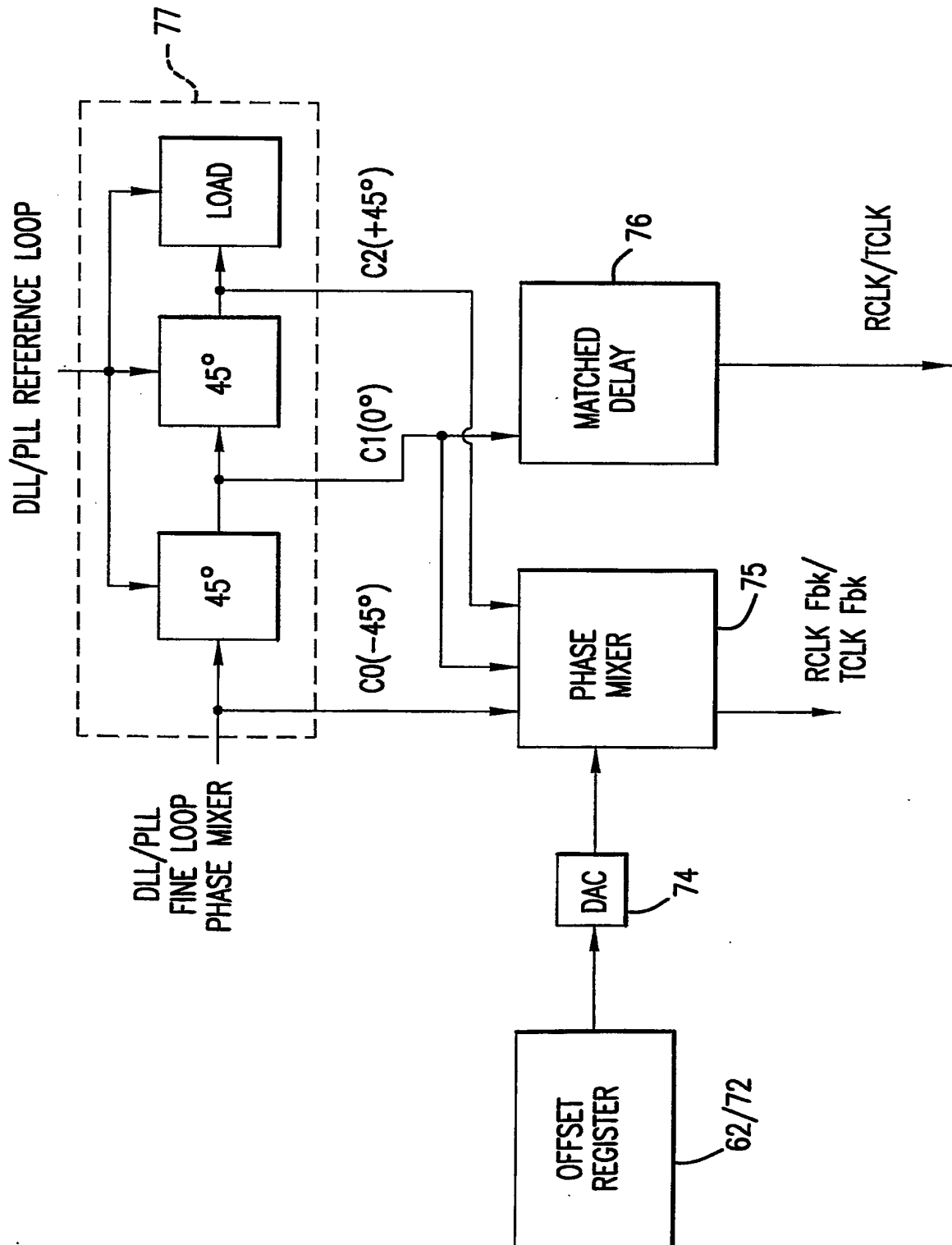


FIG. 7

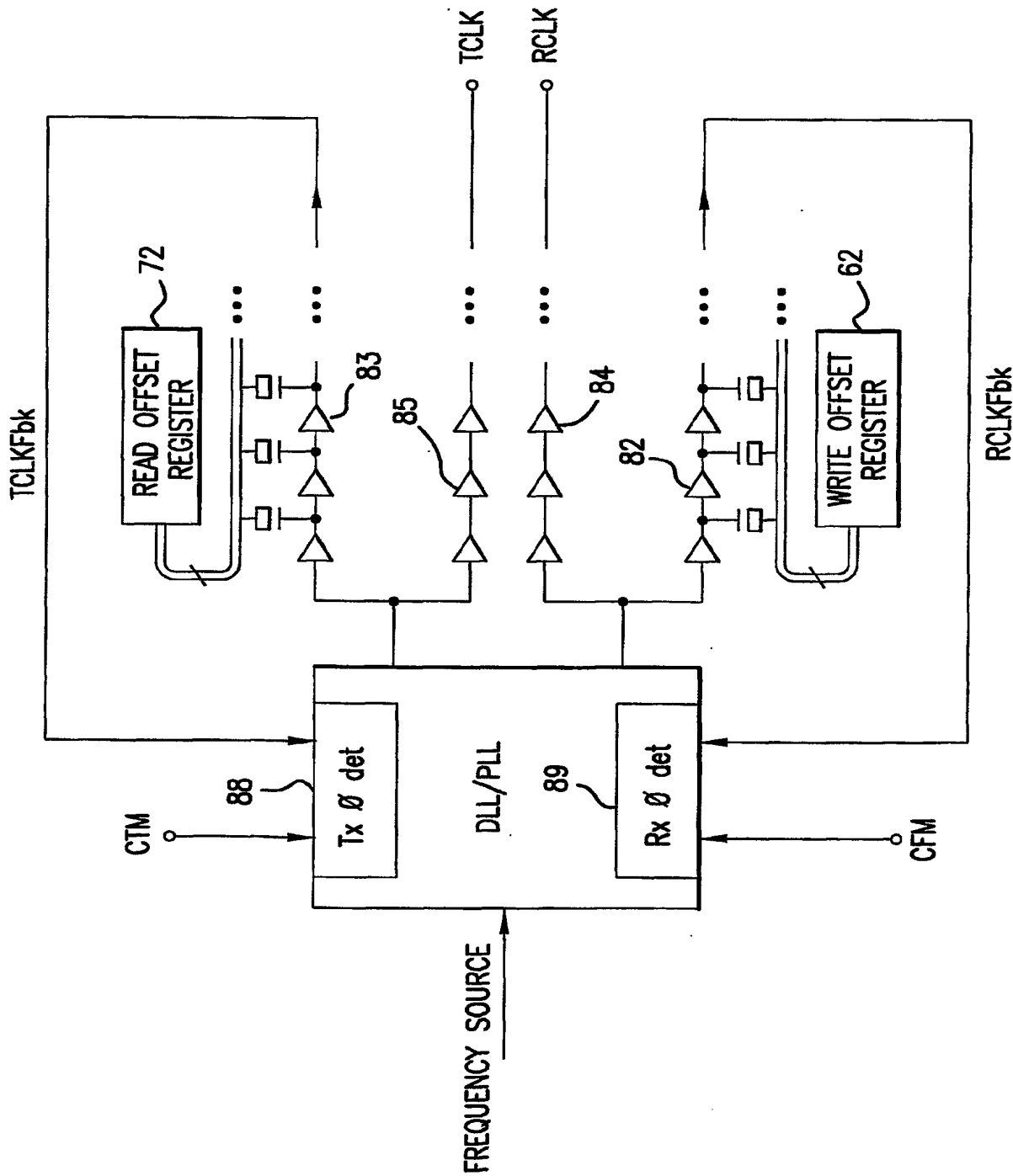


FIG.8

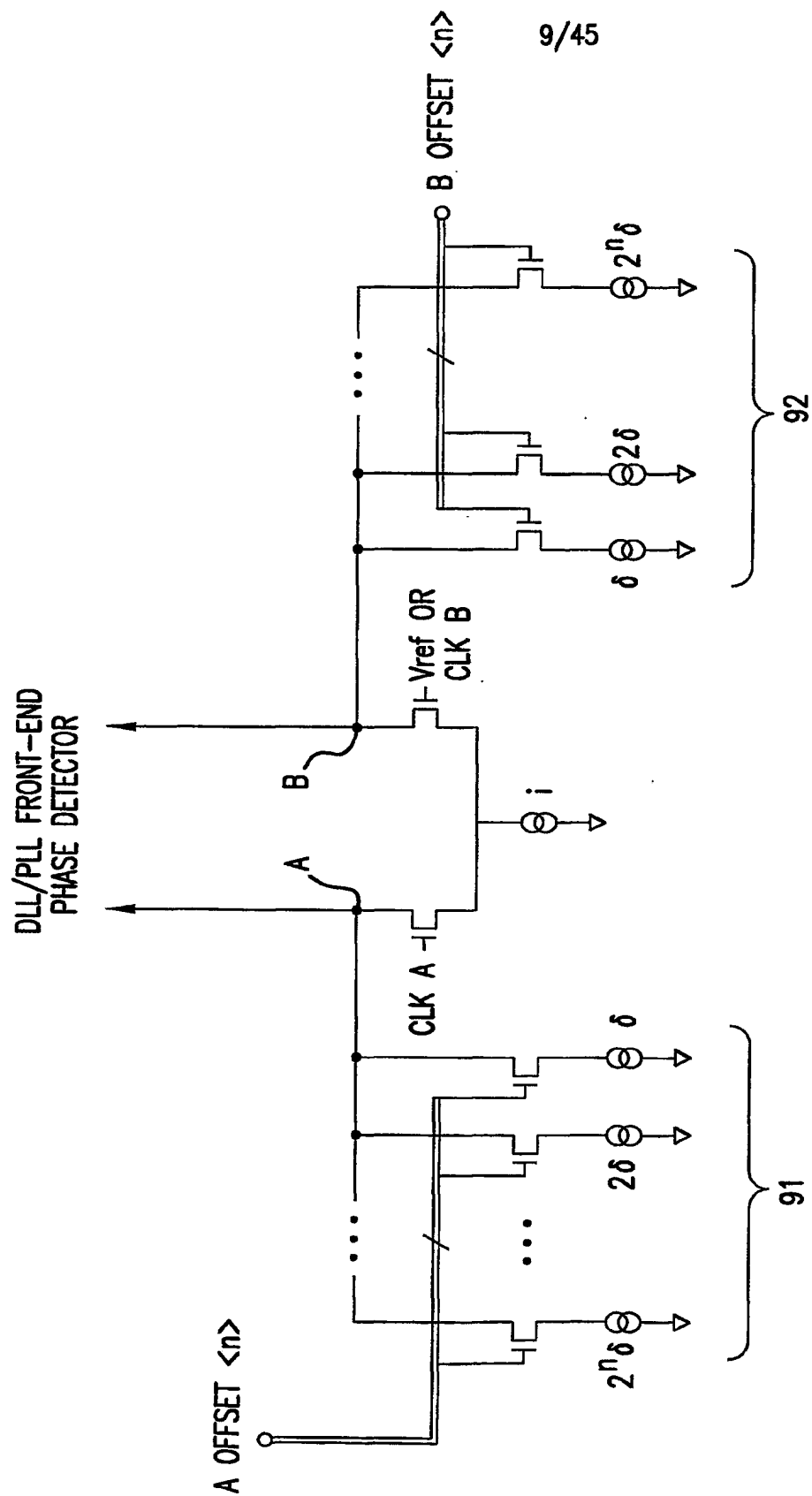


FIG. 9

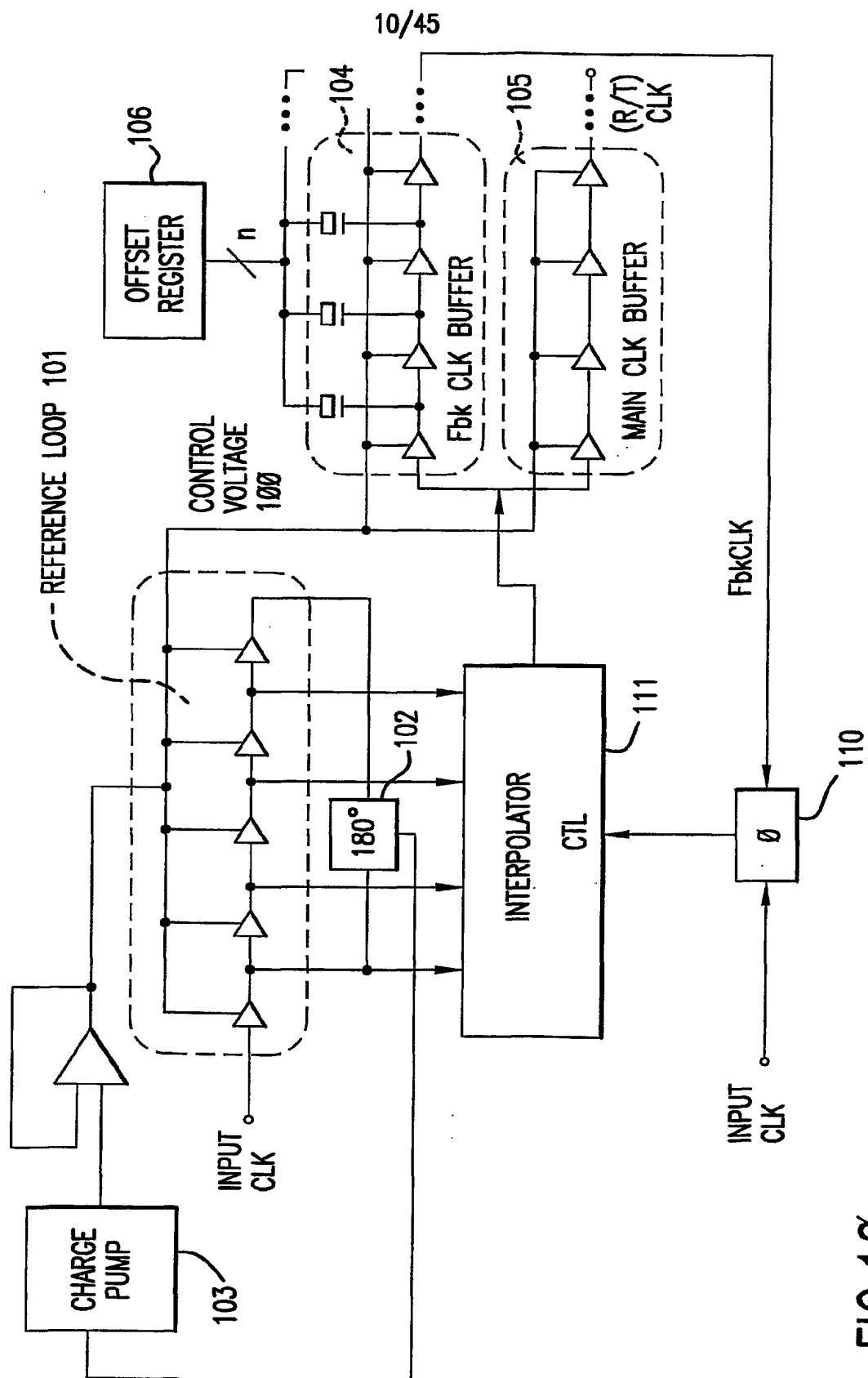


FIG. 10

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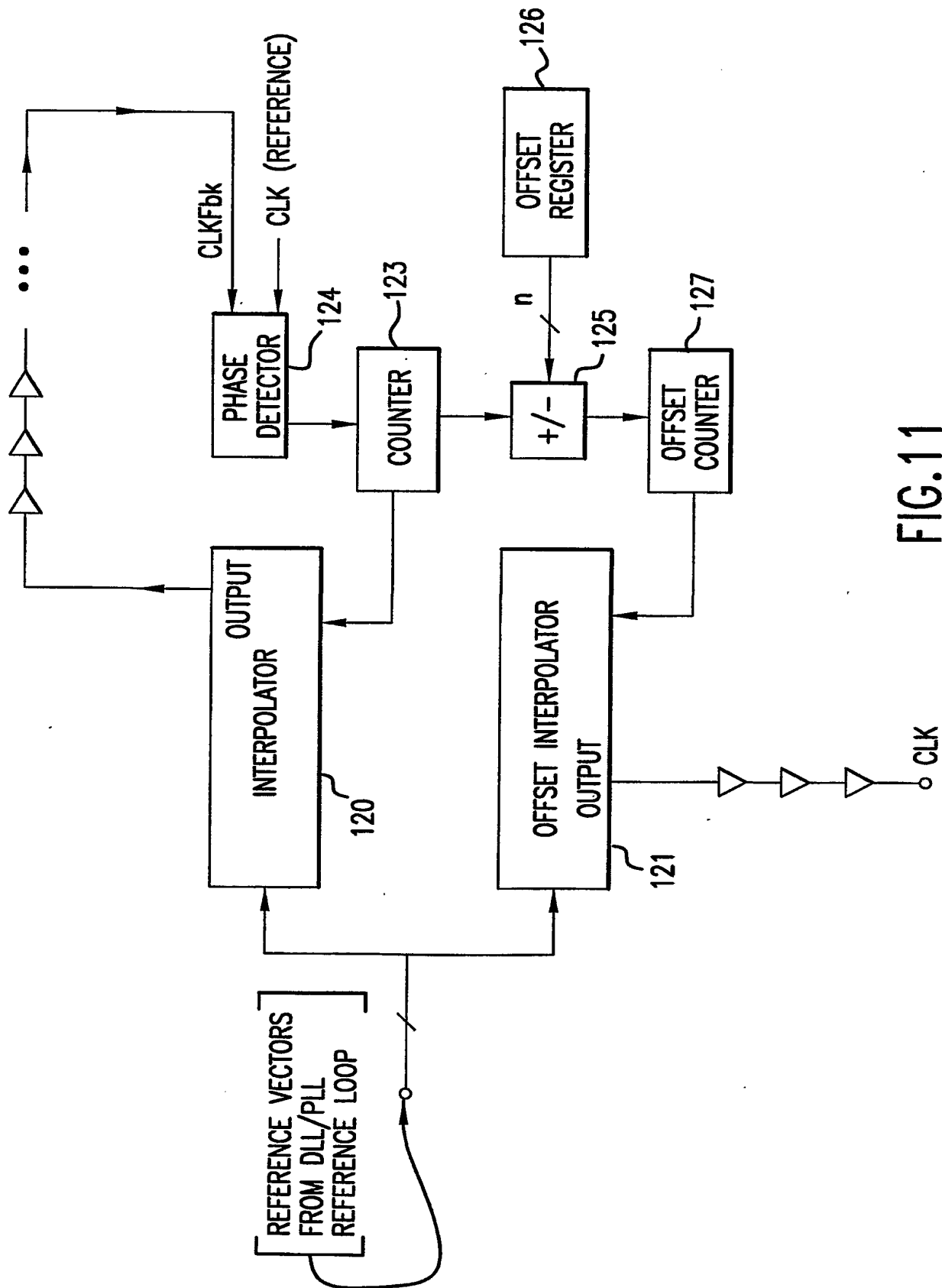


FIG.11

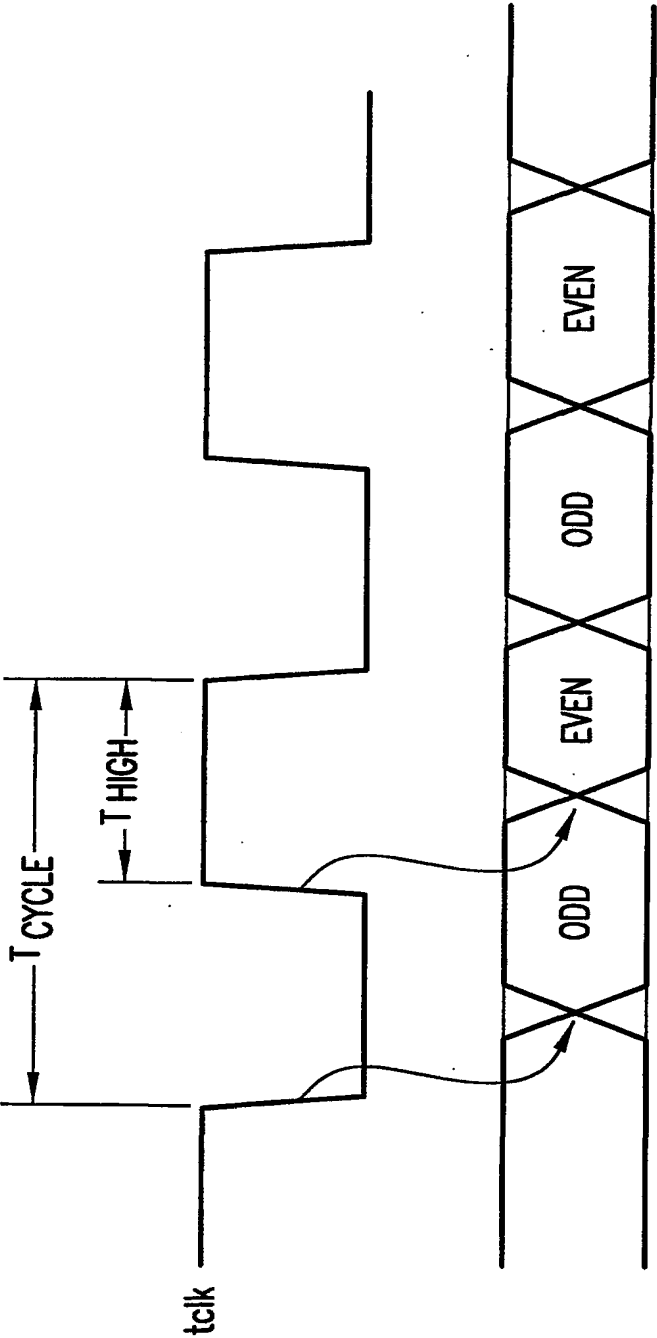


FIG.12A

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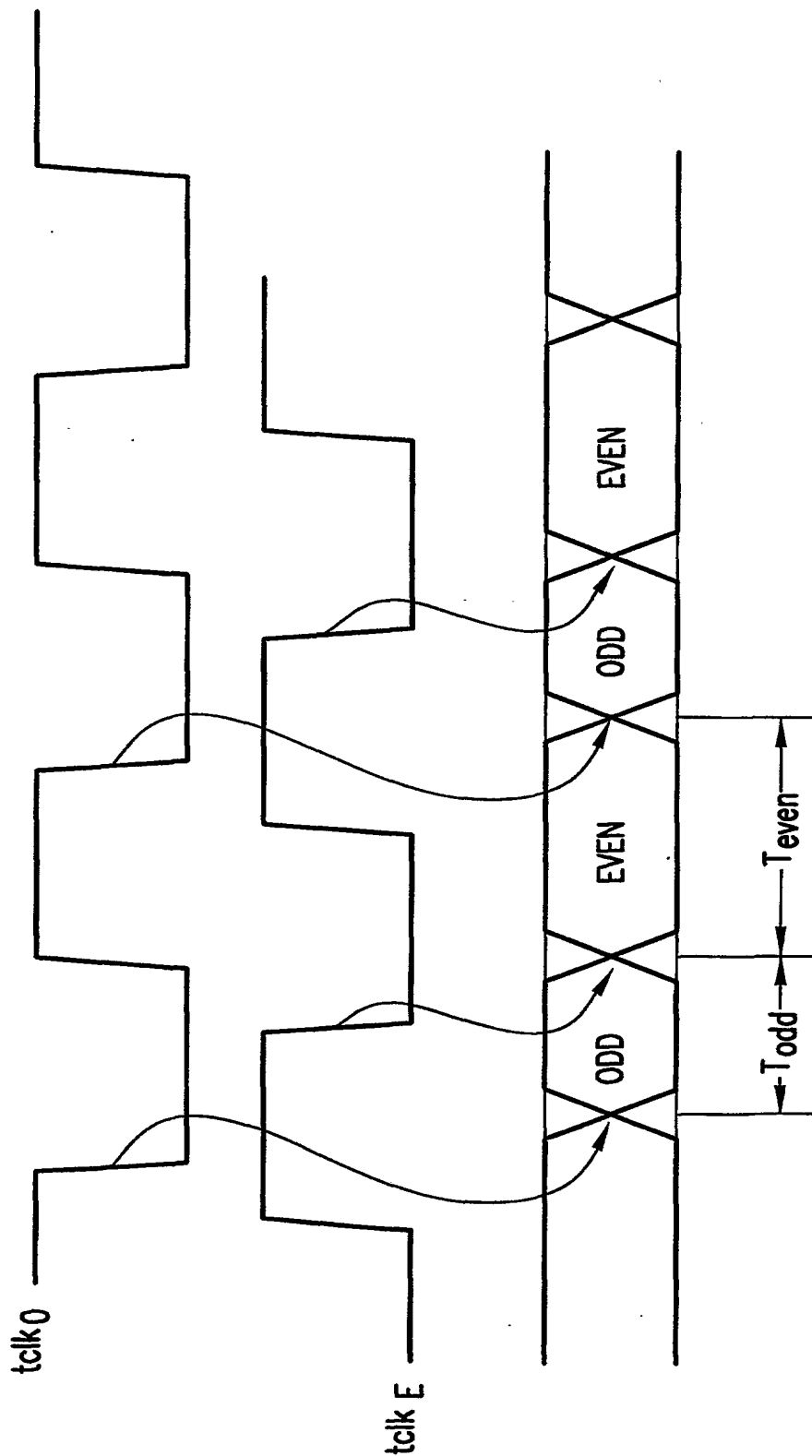


FIG.12B

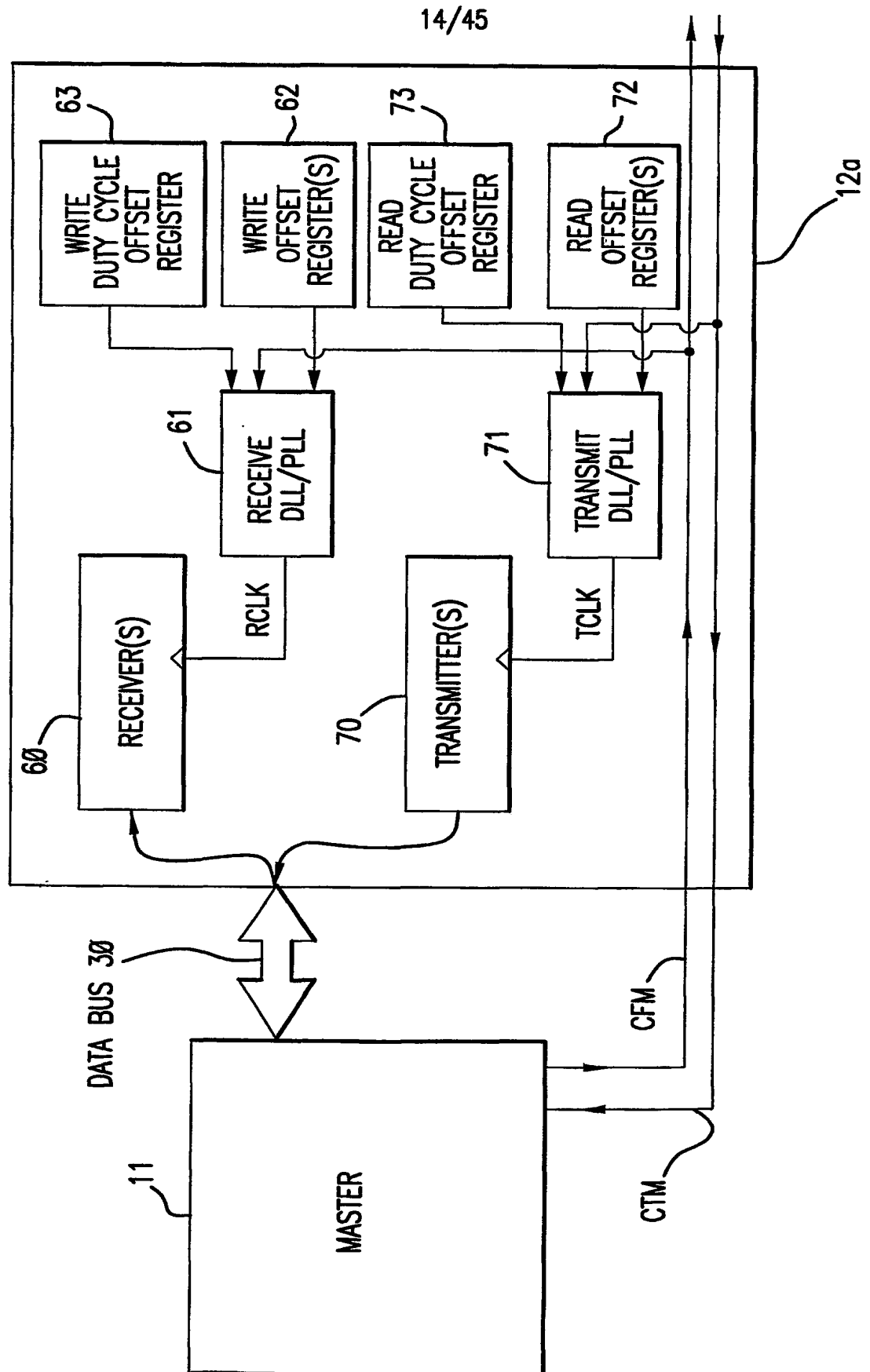


FIG.13

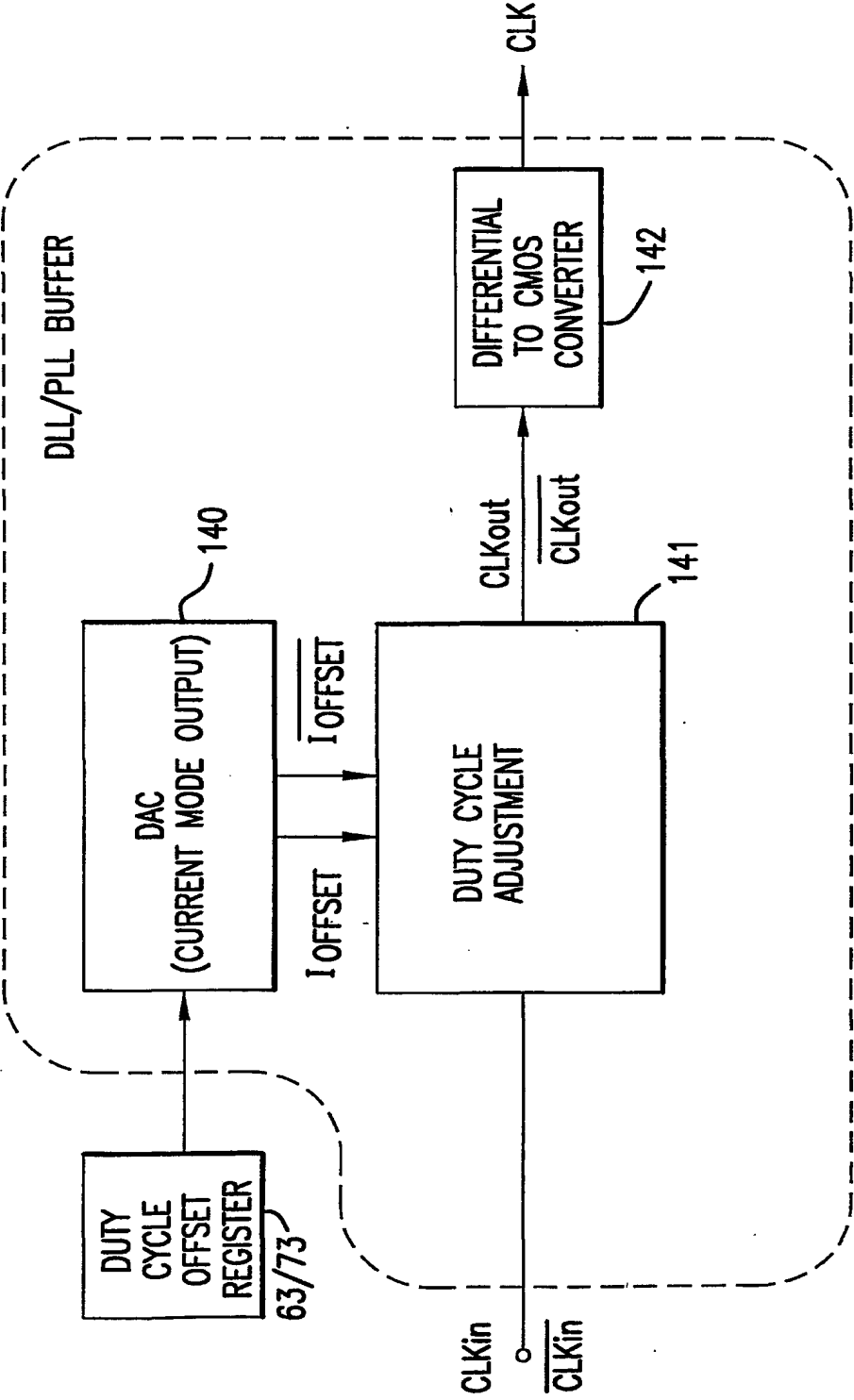


FIG.14

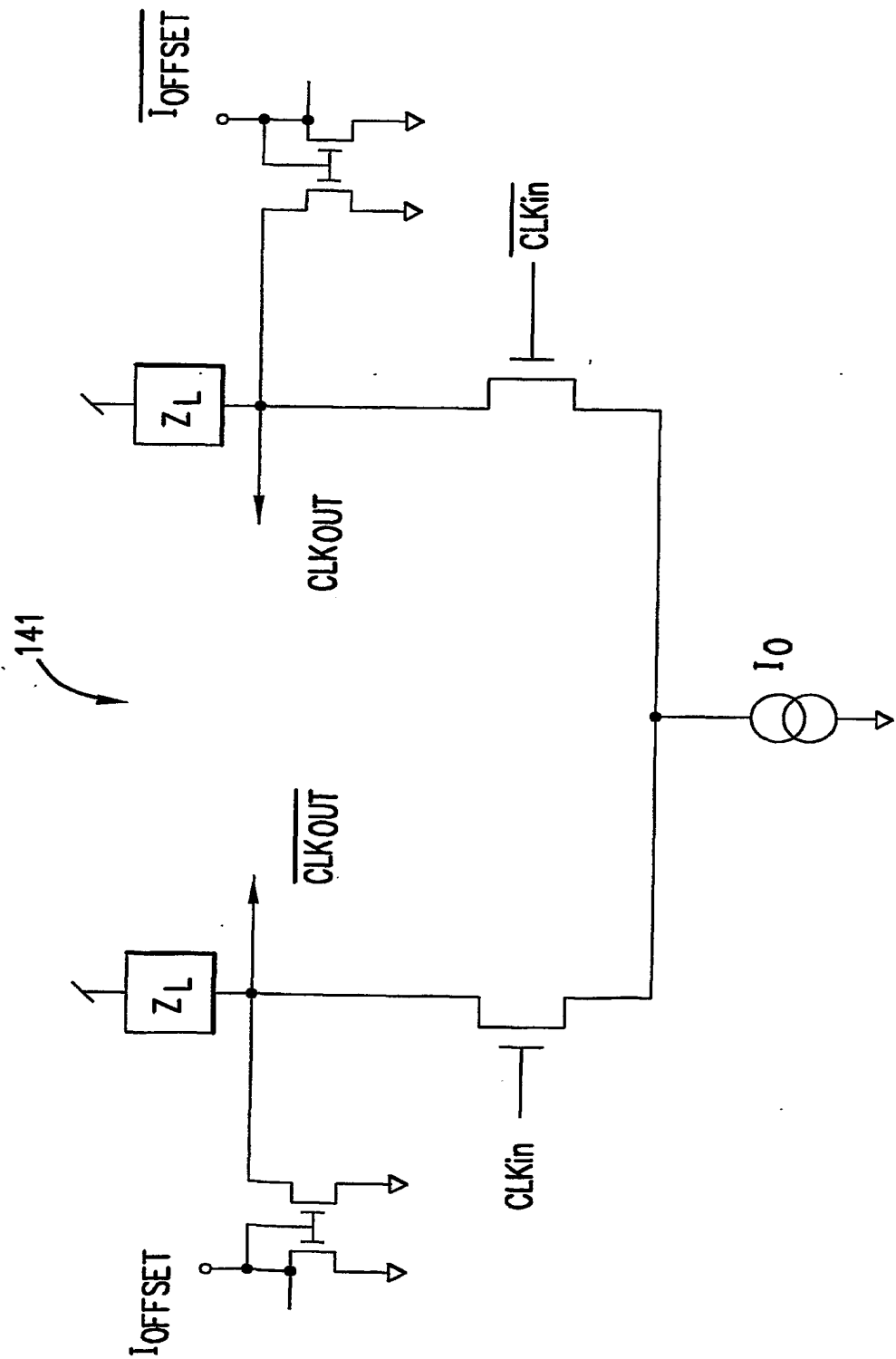


FIG.15

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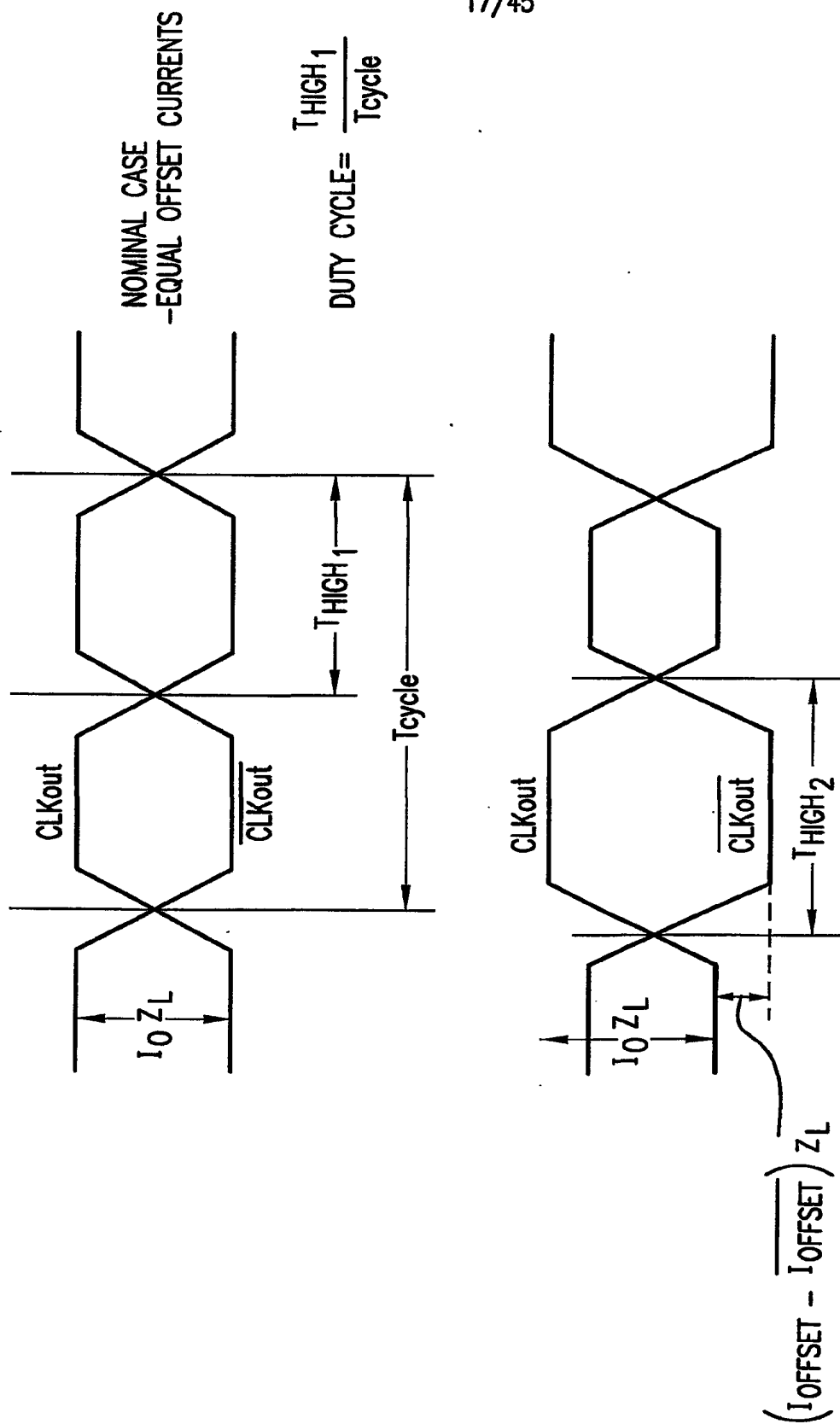


FIG.16

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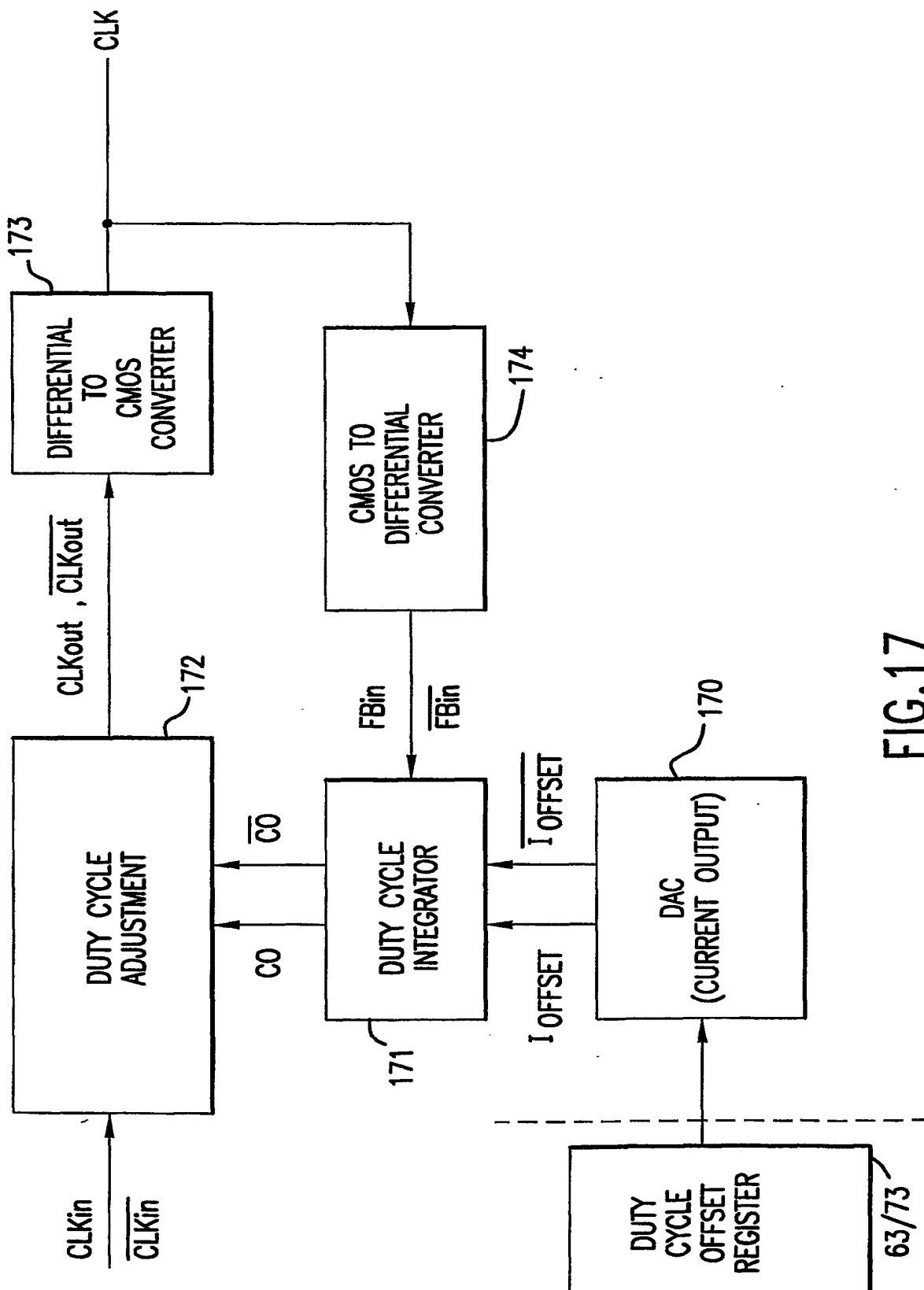


FIG.17

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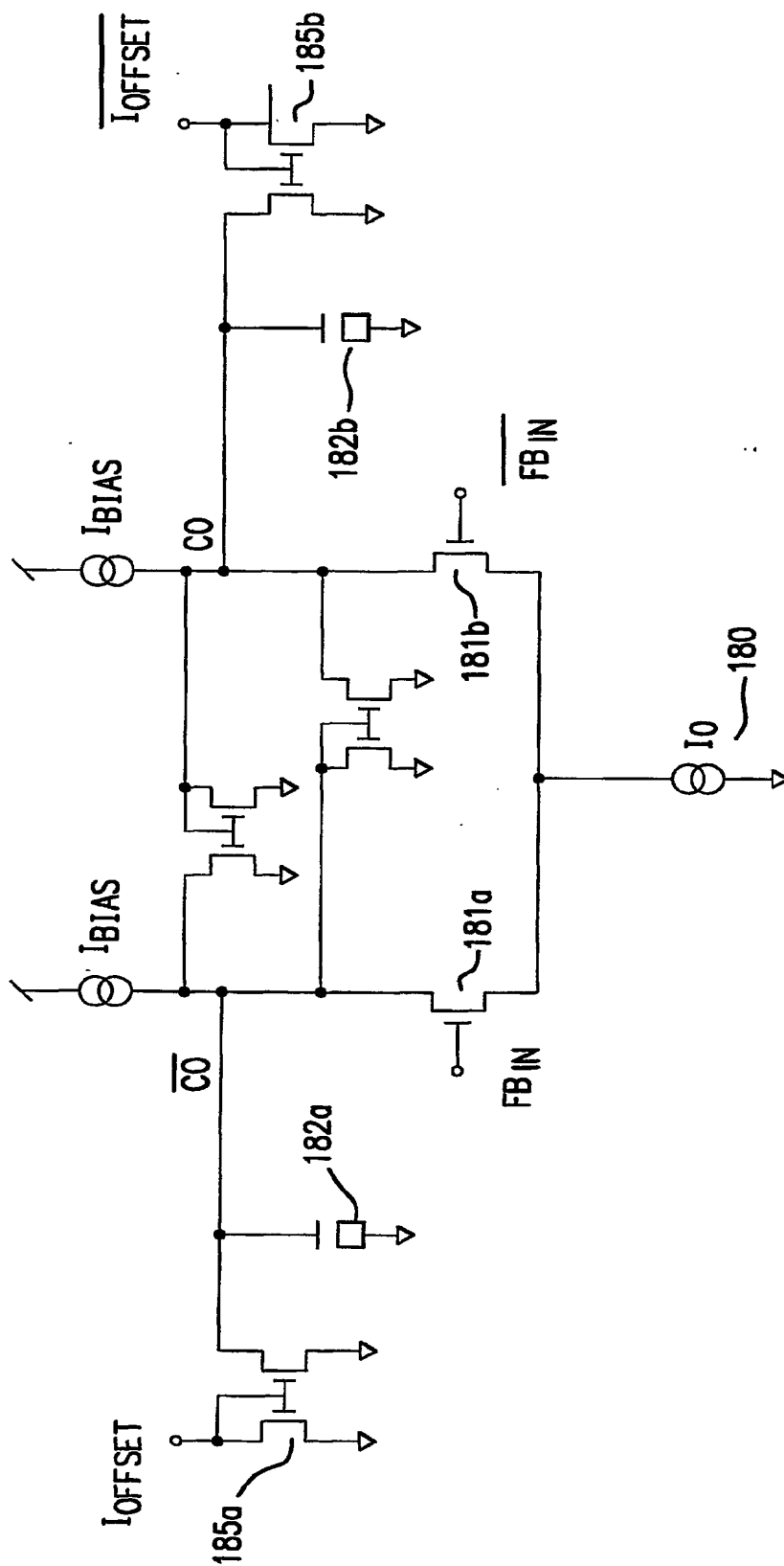


FIG.18

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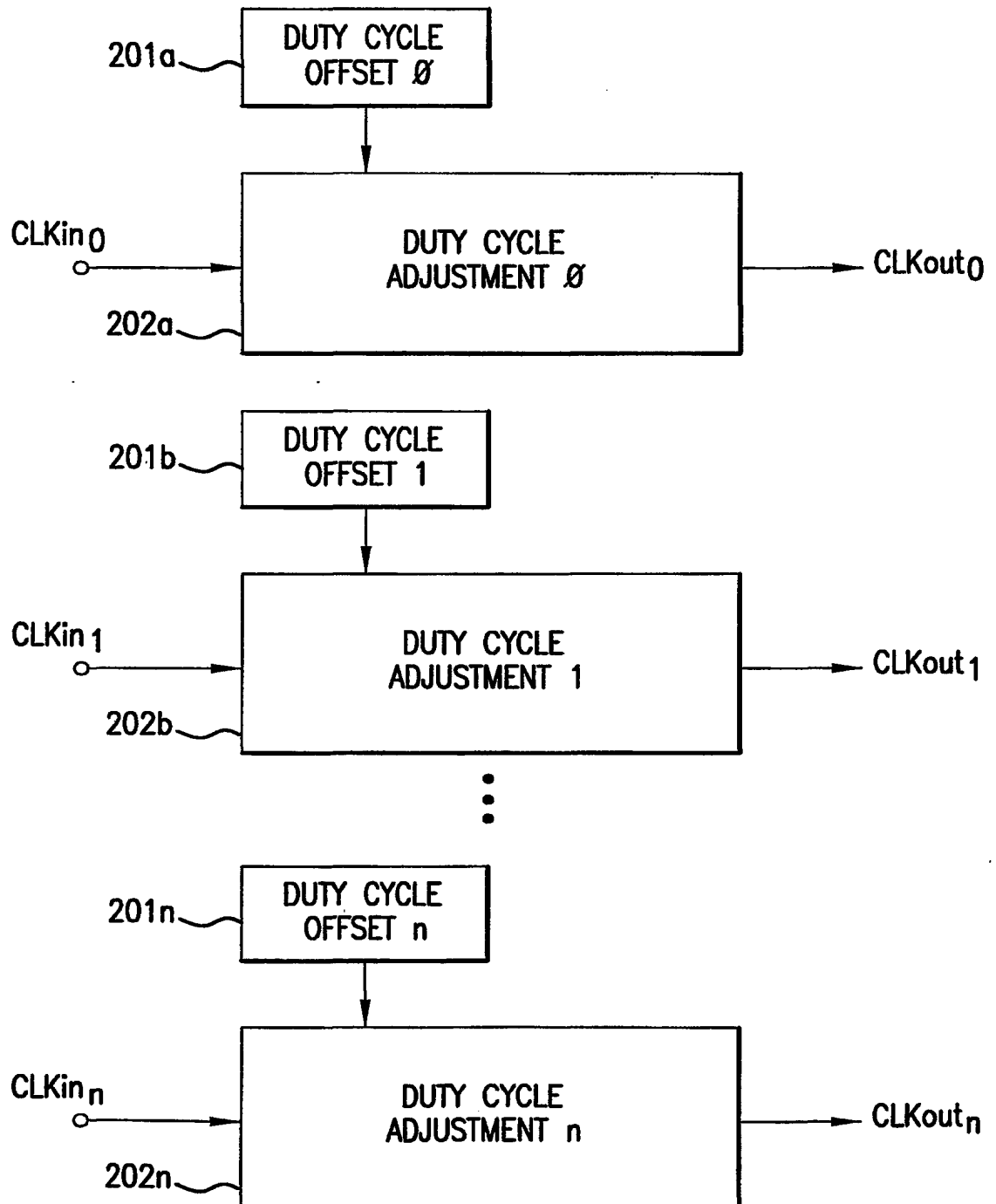


FIG.20

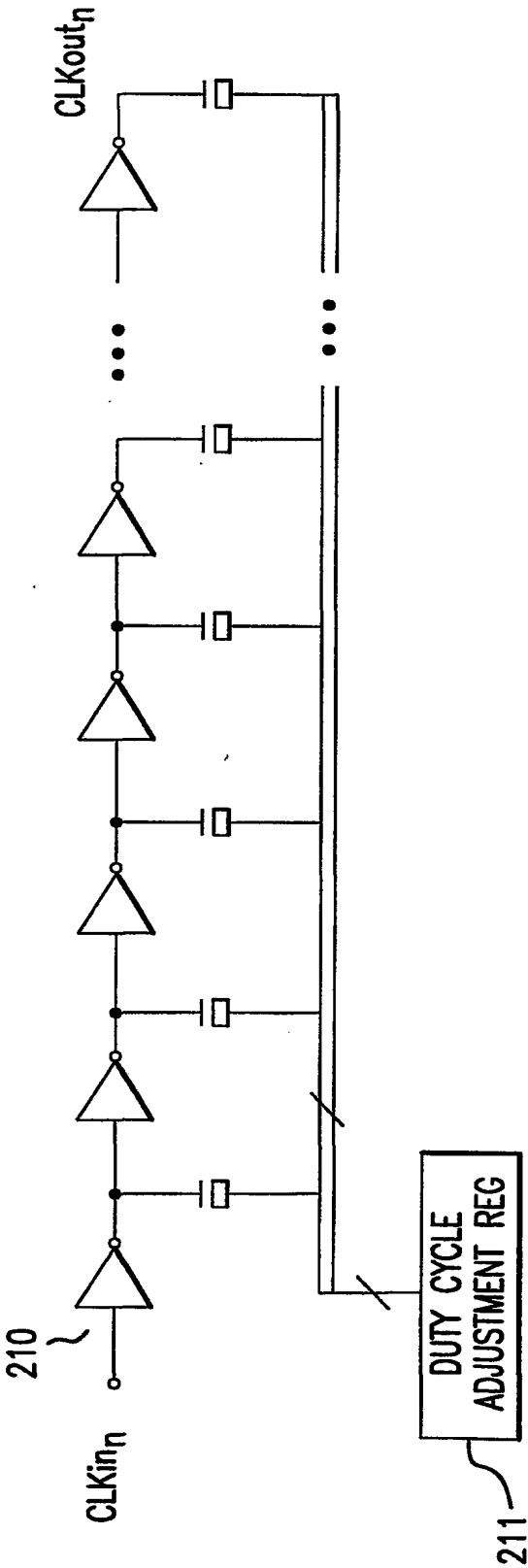


FIG.21

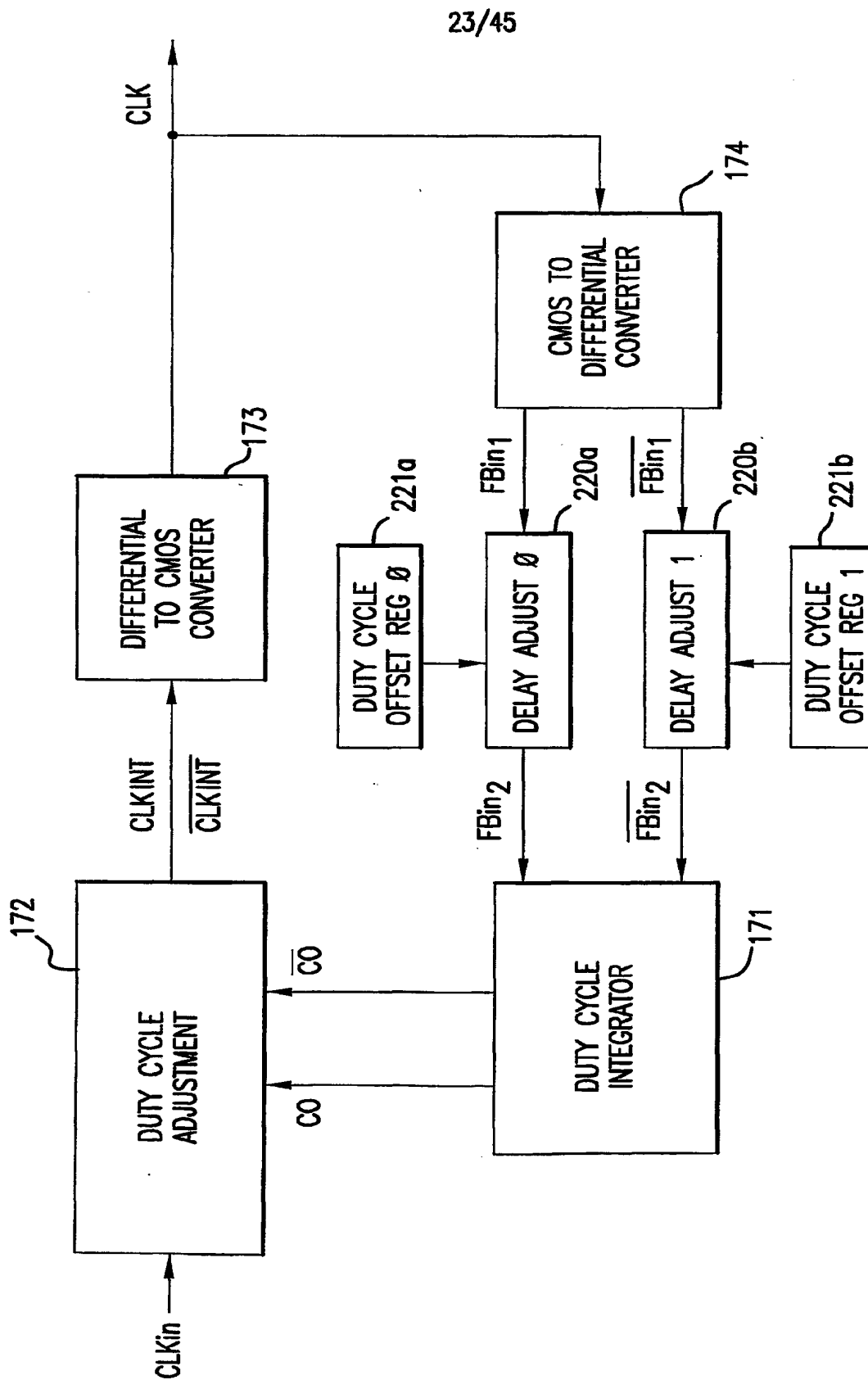


FIG.22

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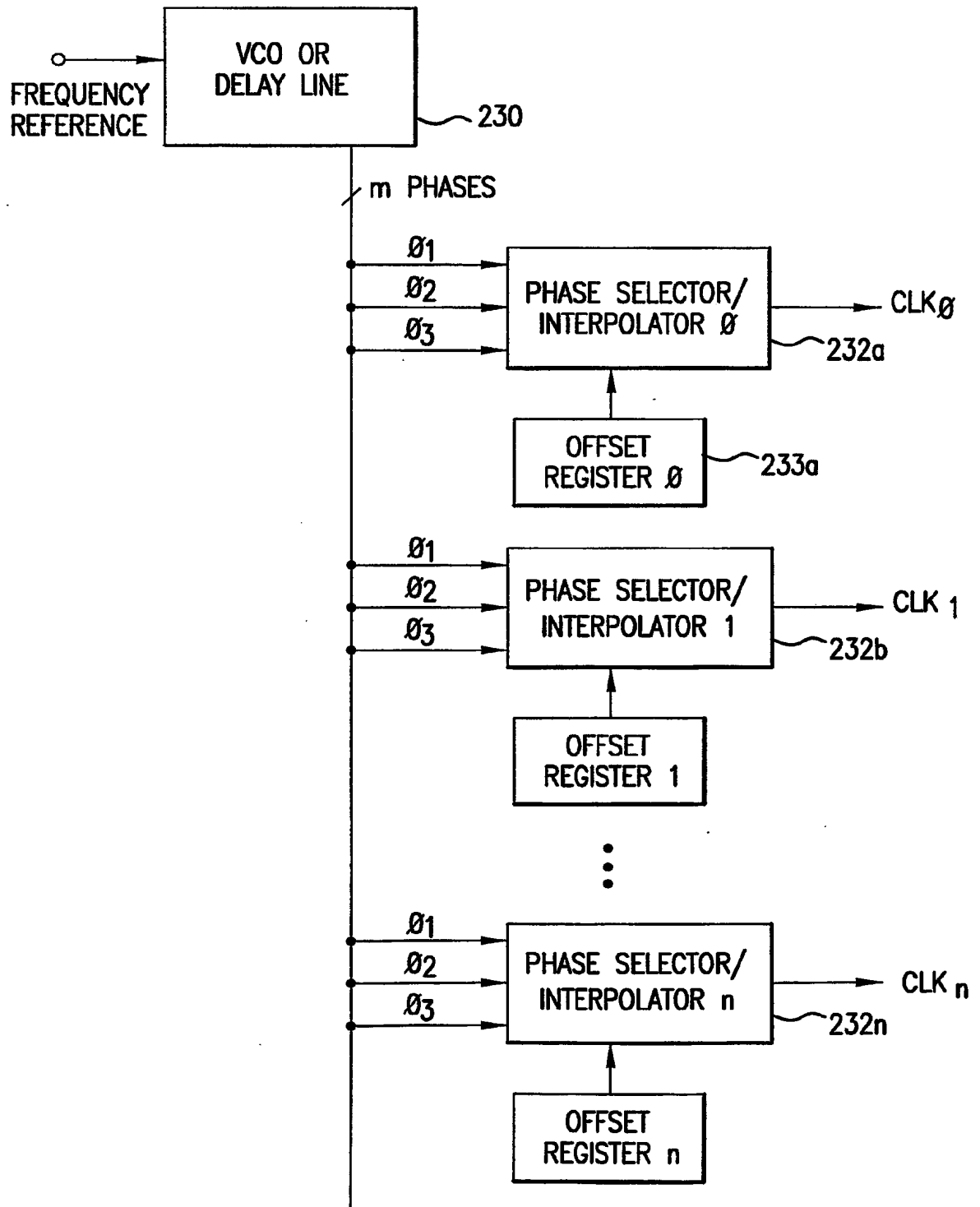


FIG. 23

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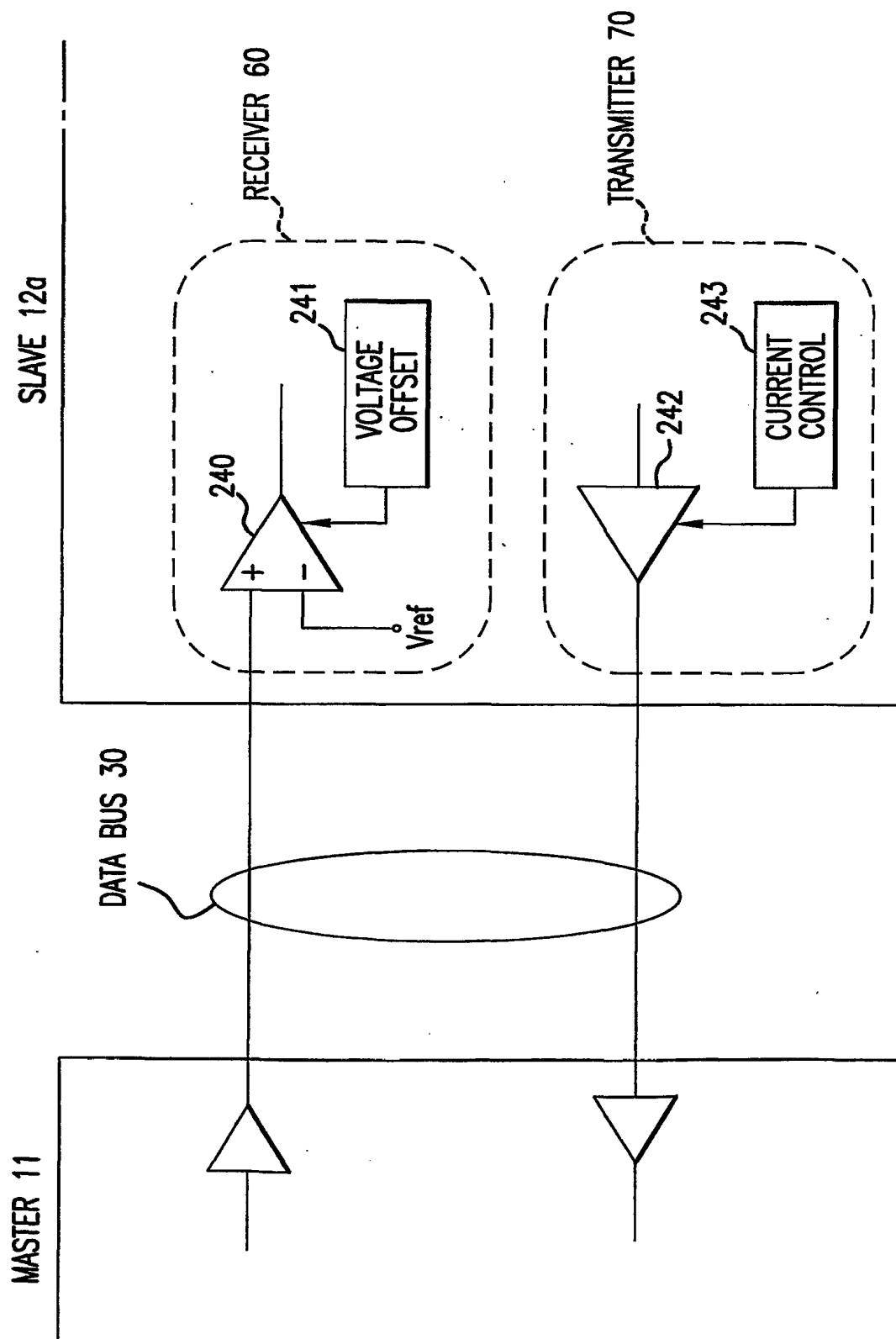


FIG.24

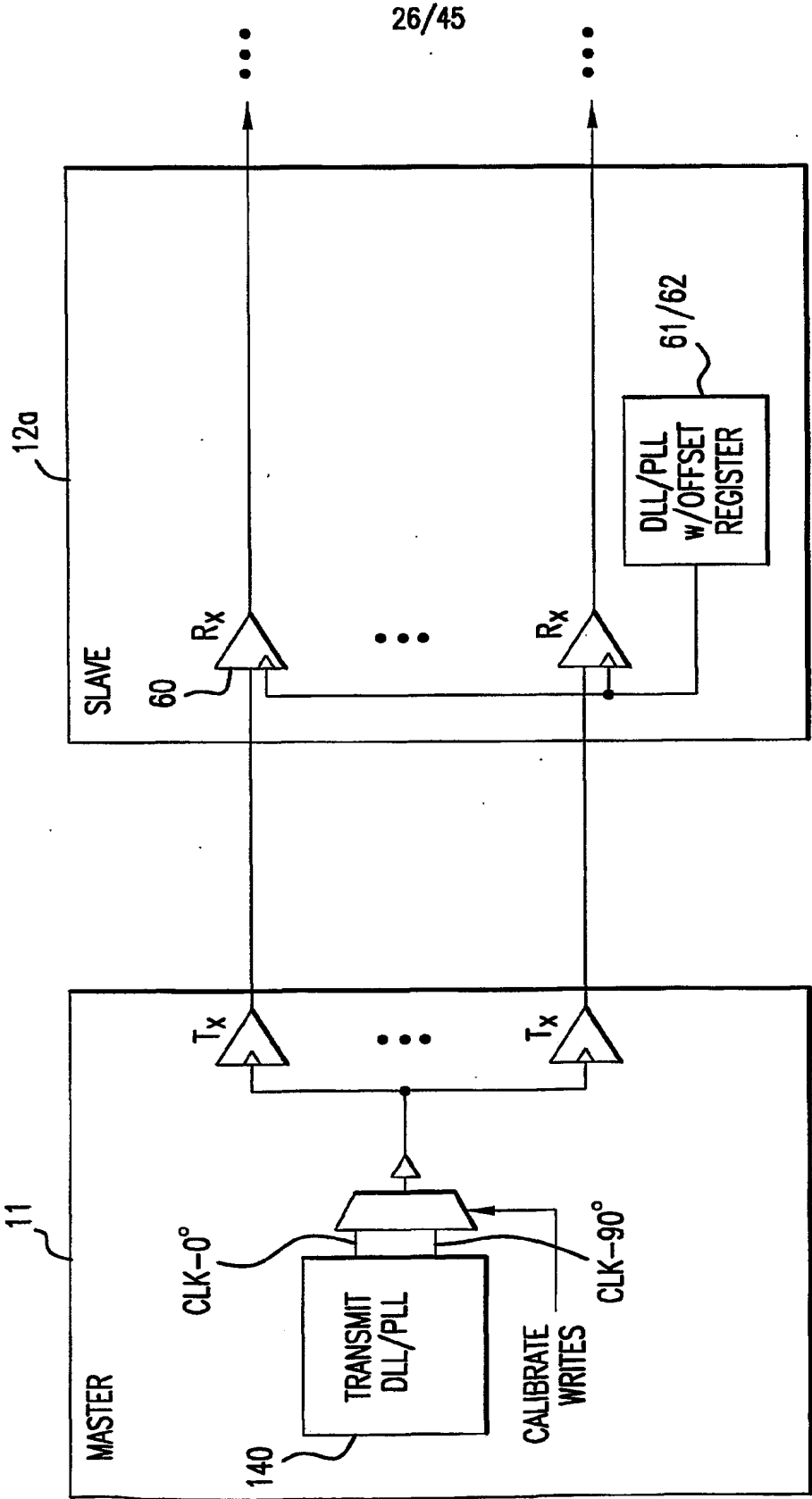


FIG.25

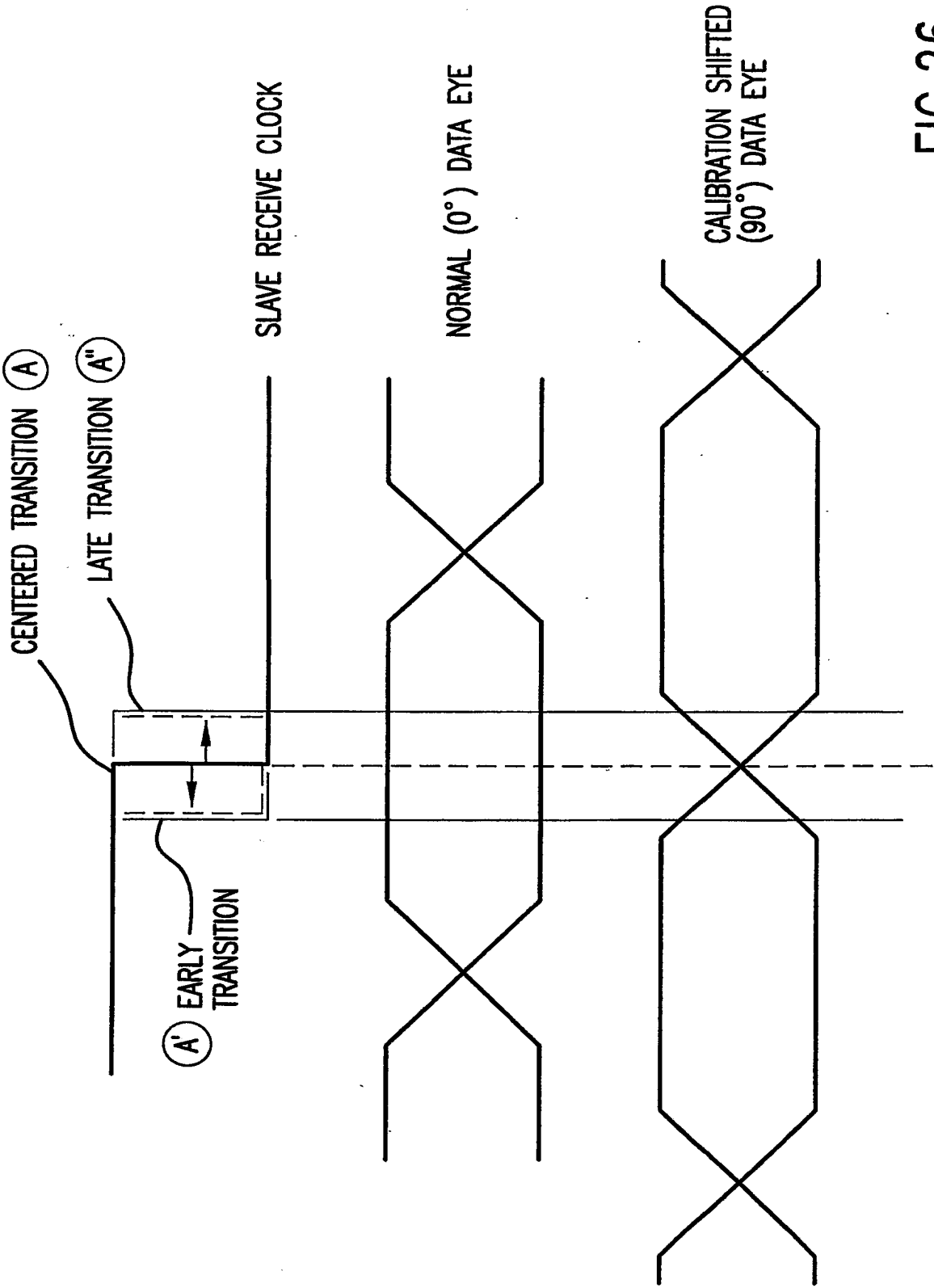


FIG.26

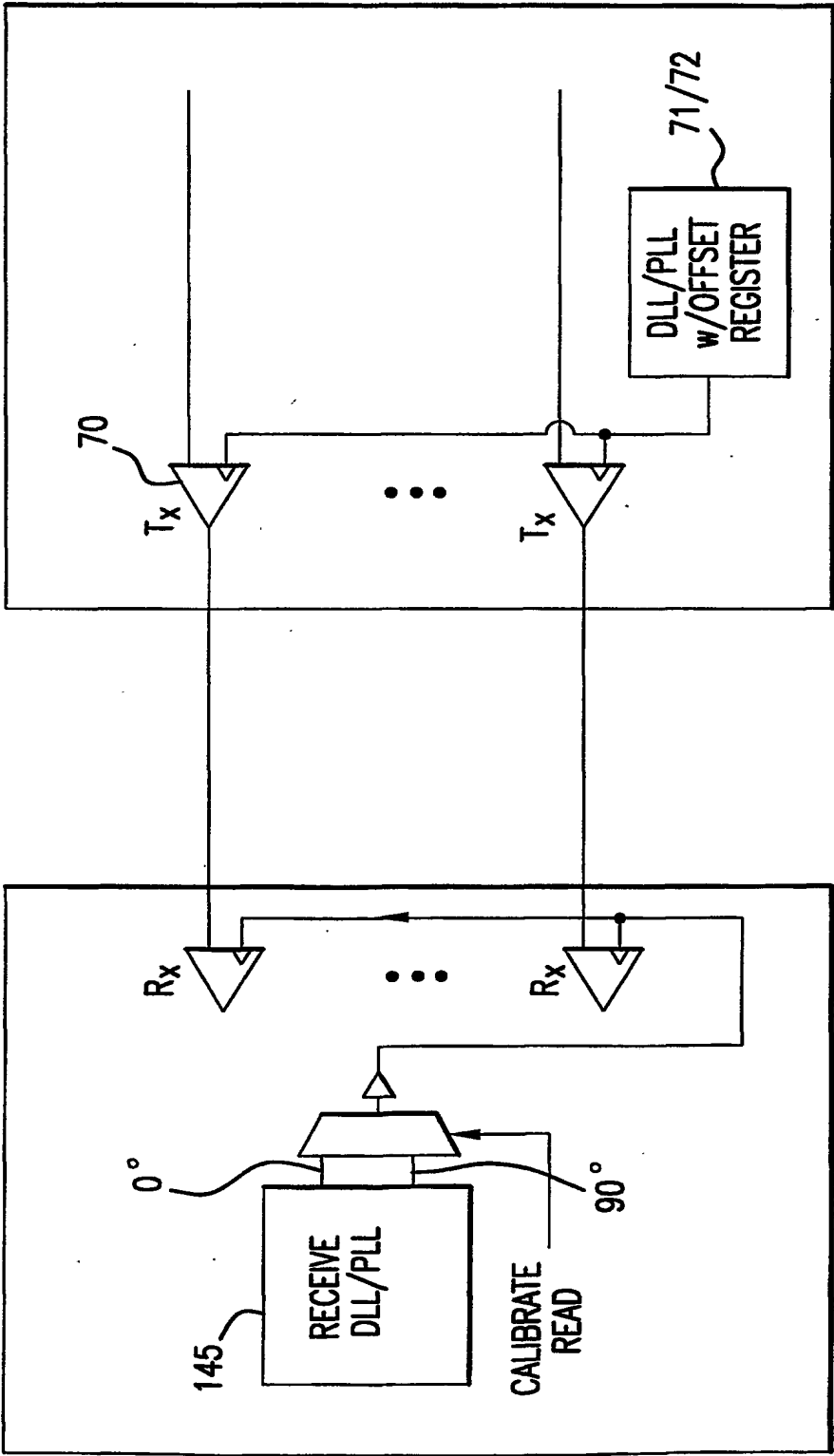


FIG.27

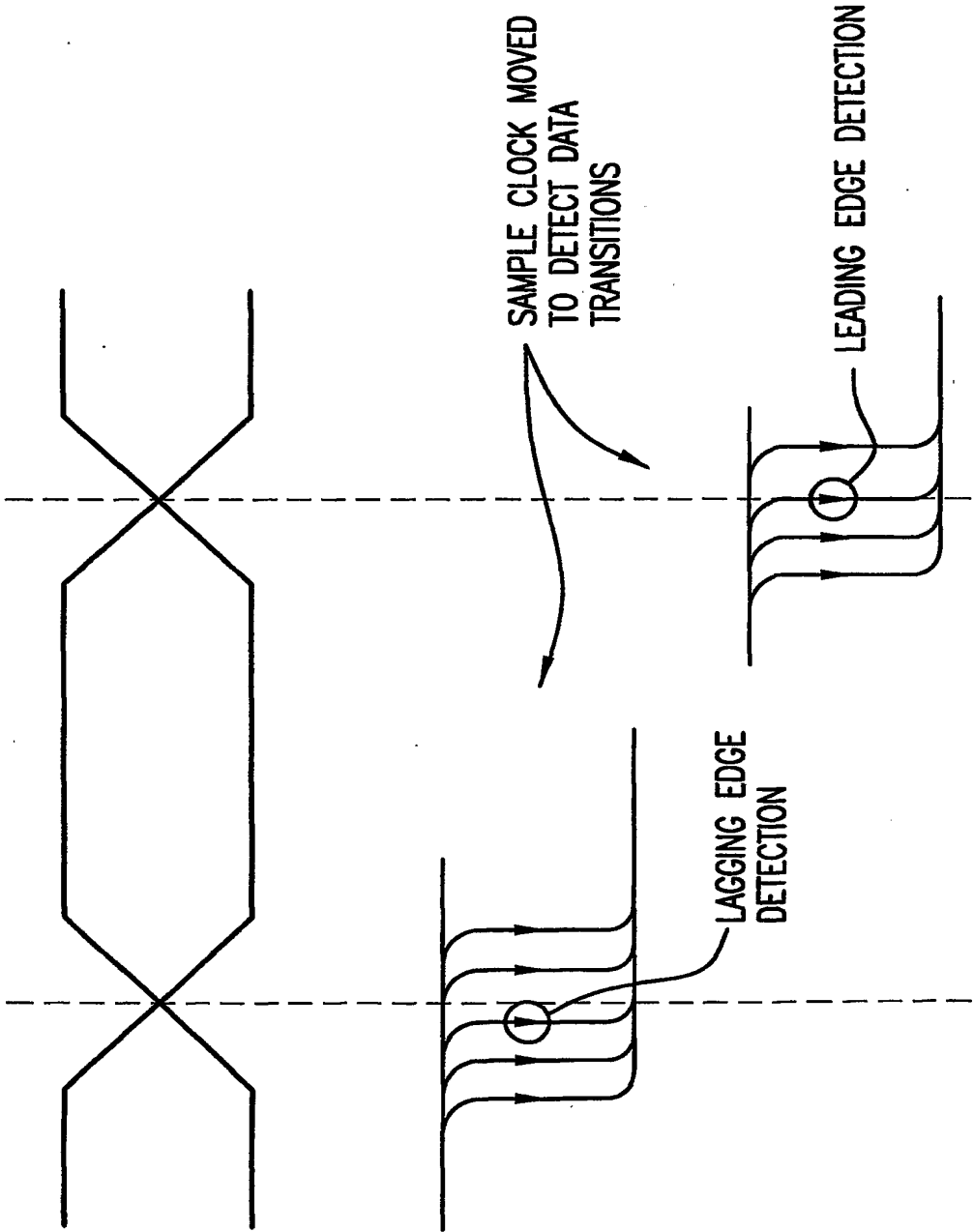


FIG. 28

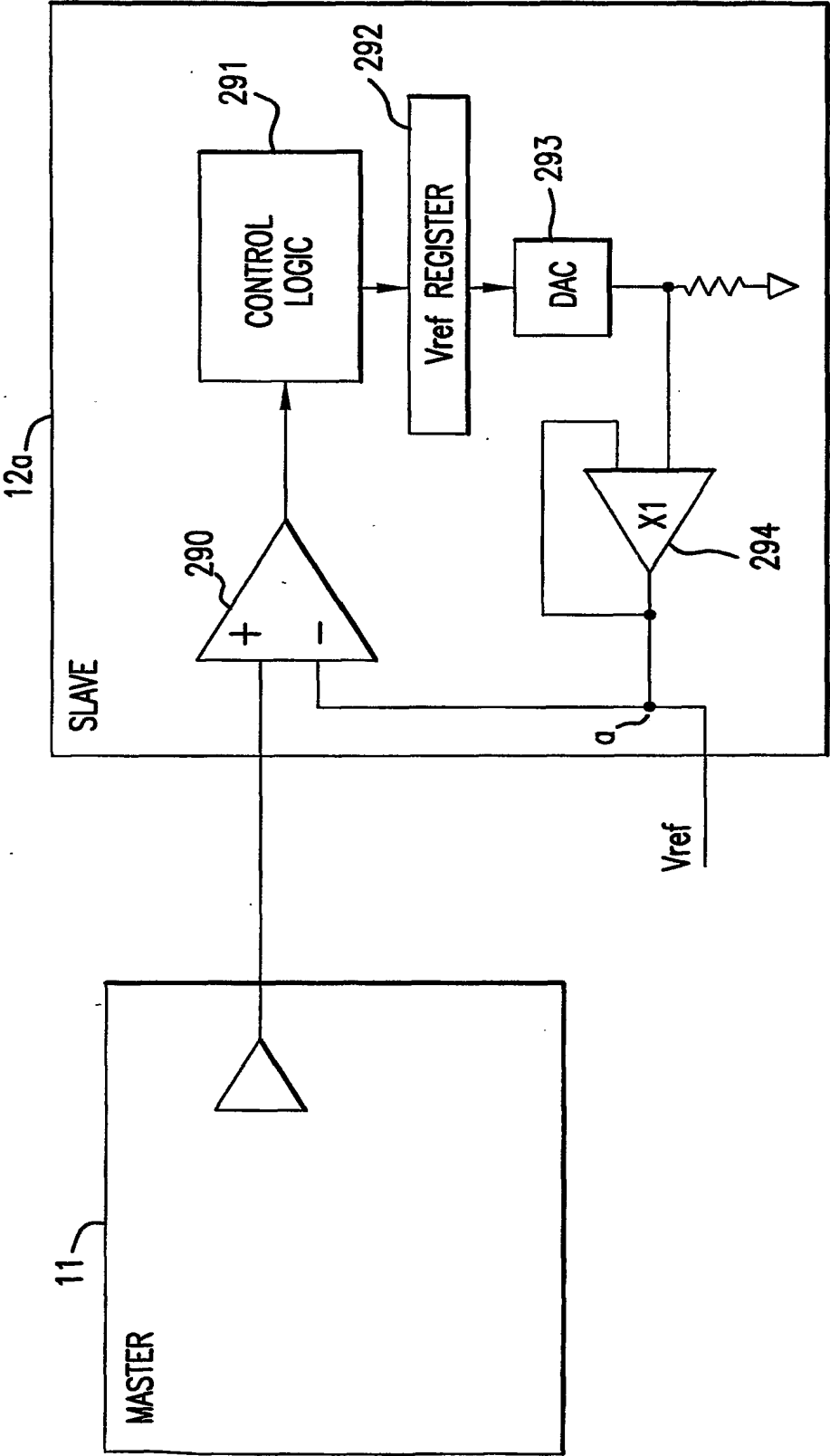


FIG.29

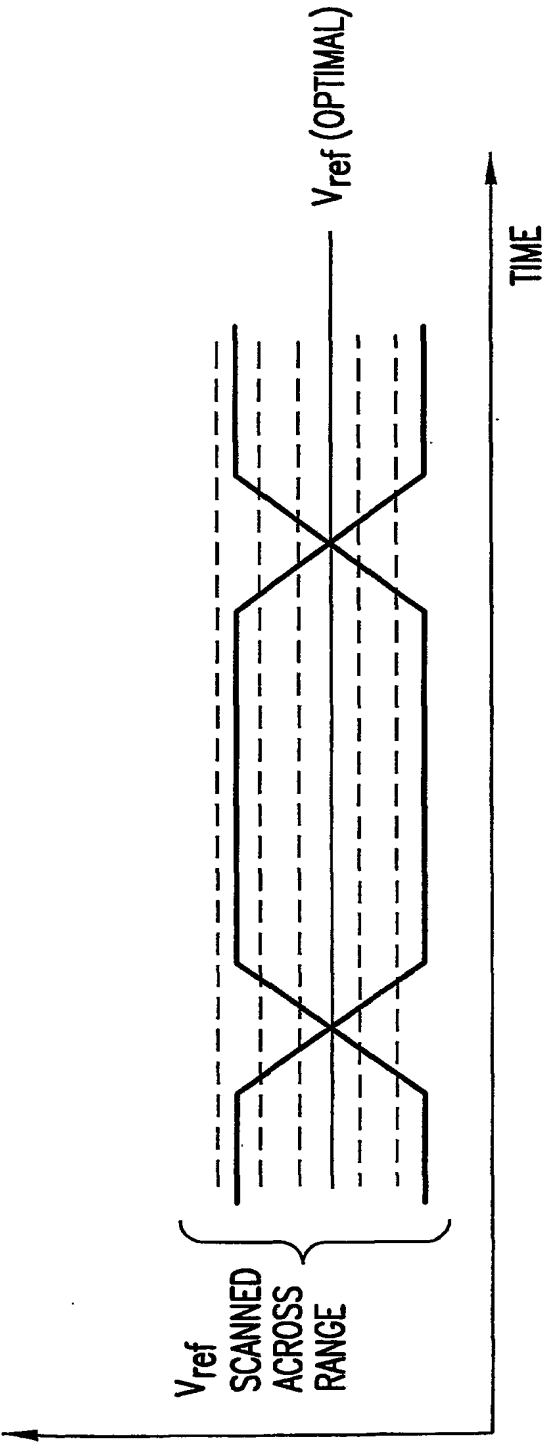


FIG.30

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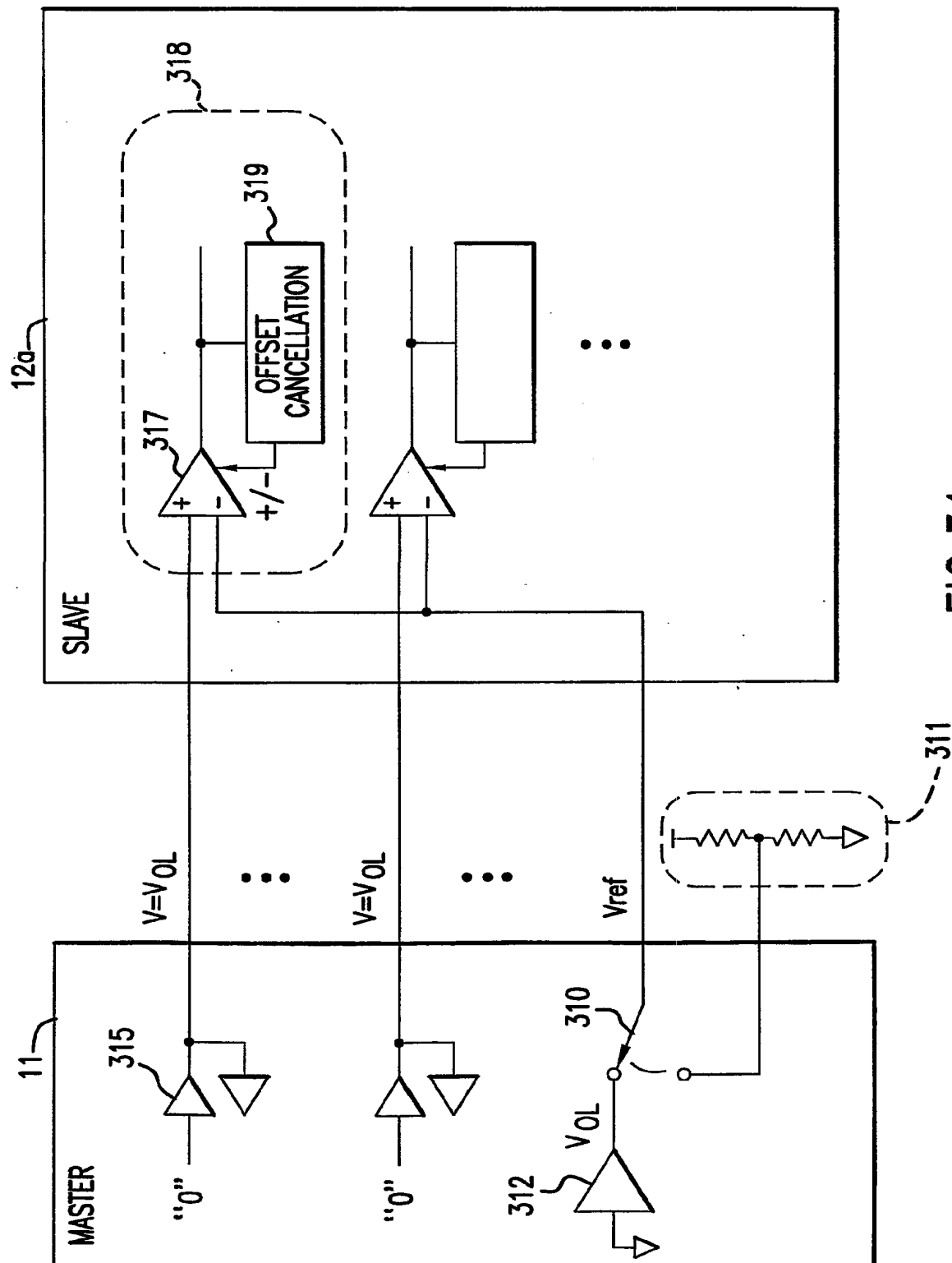


FIG. 31

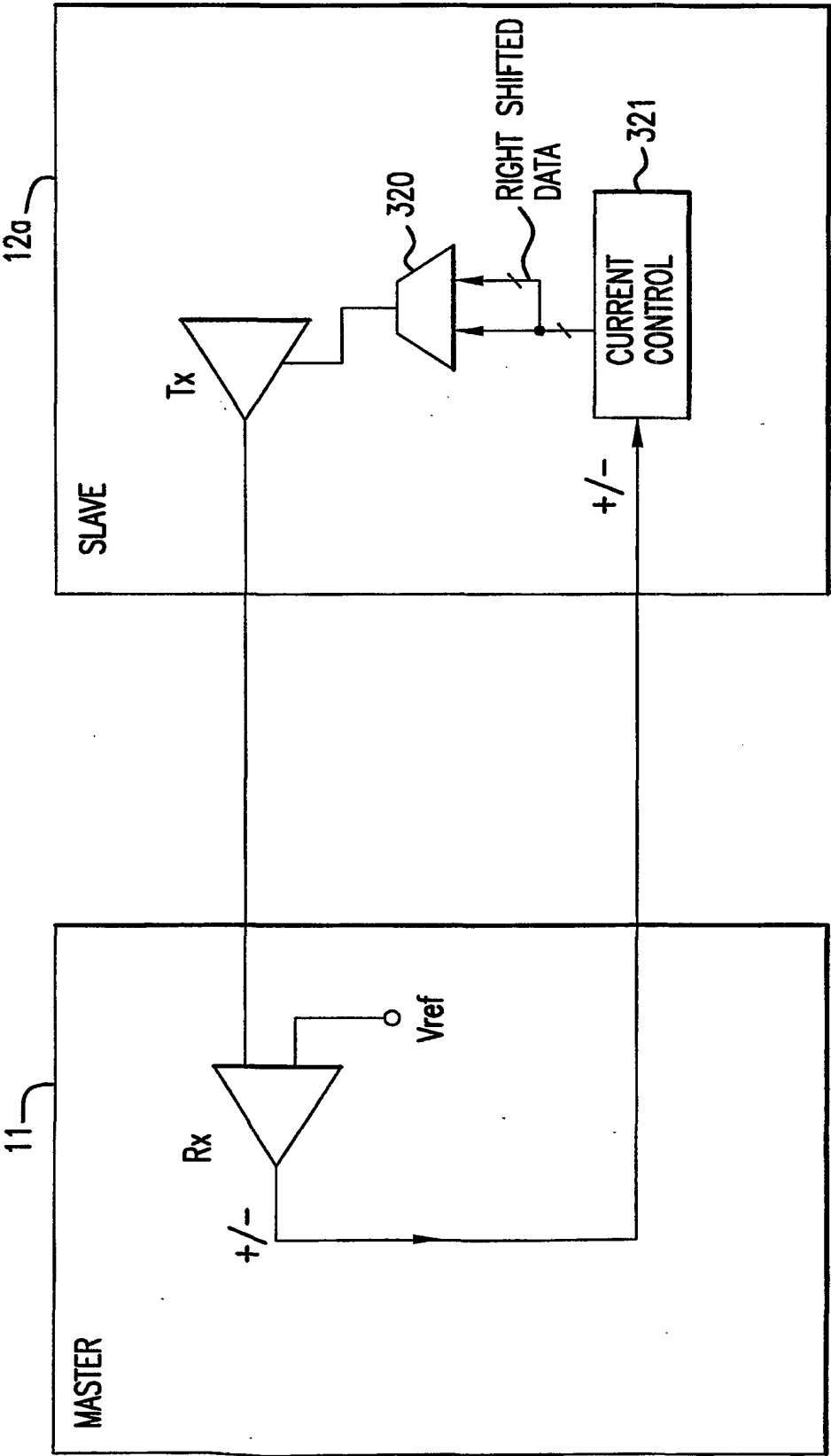


FIG.32

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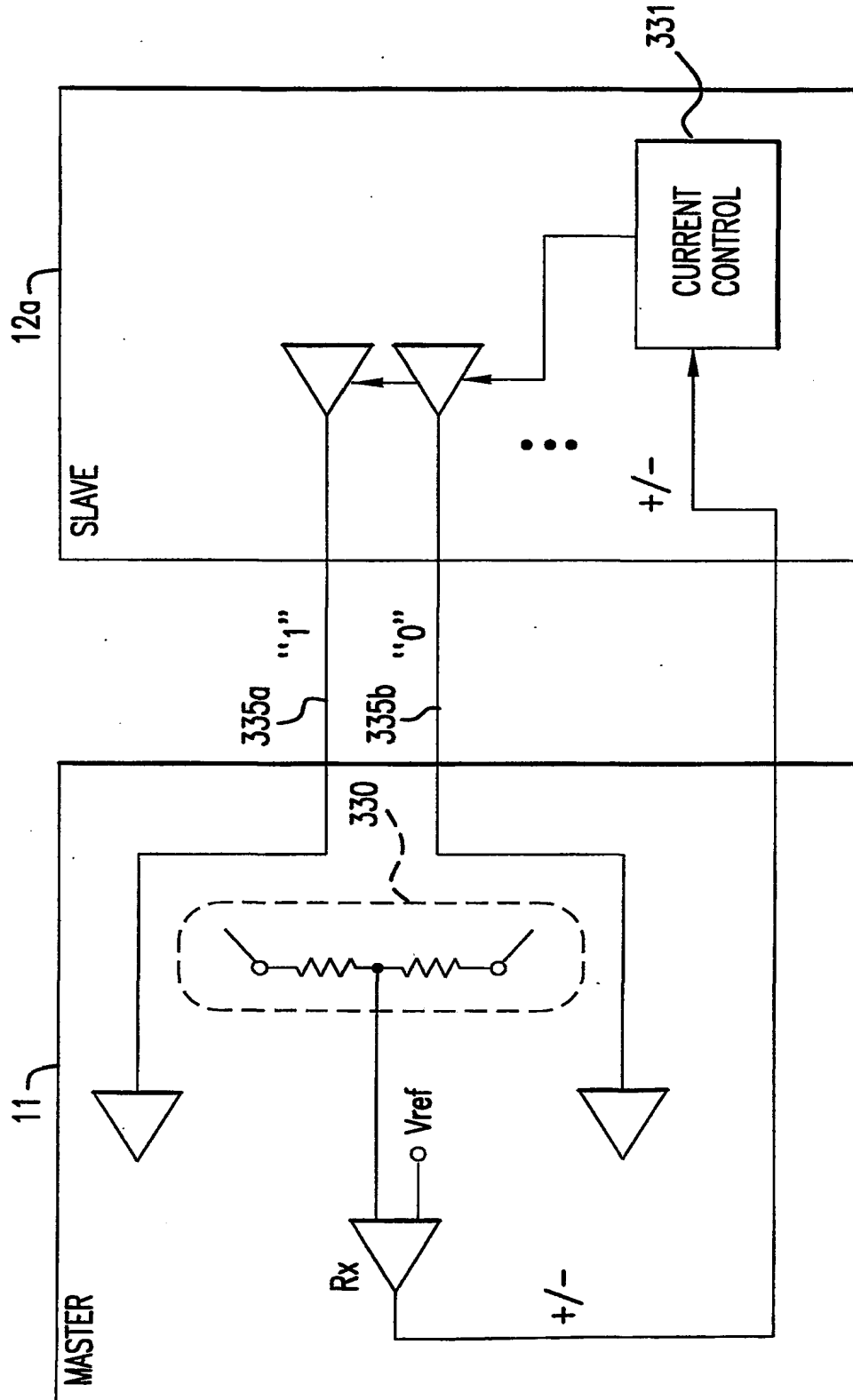


FIG. 33

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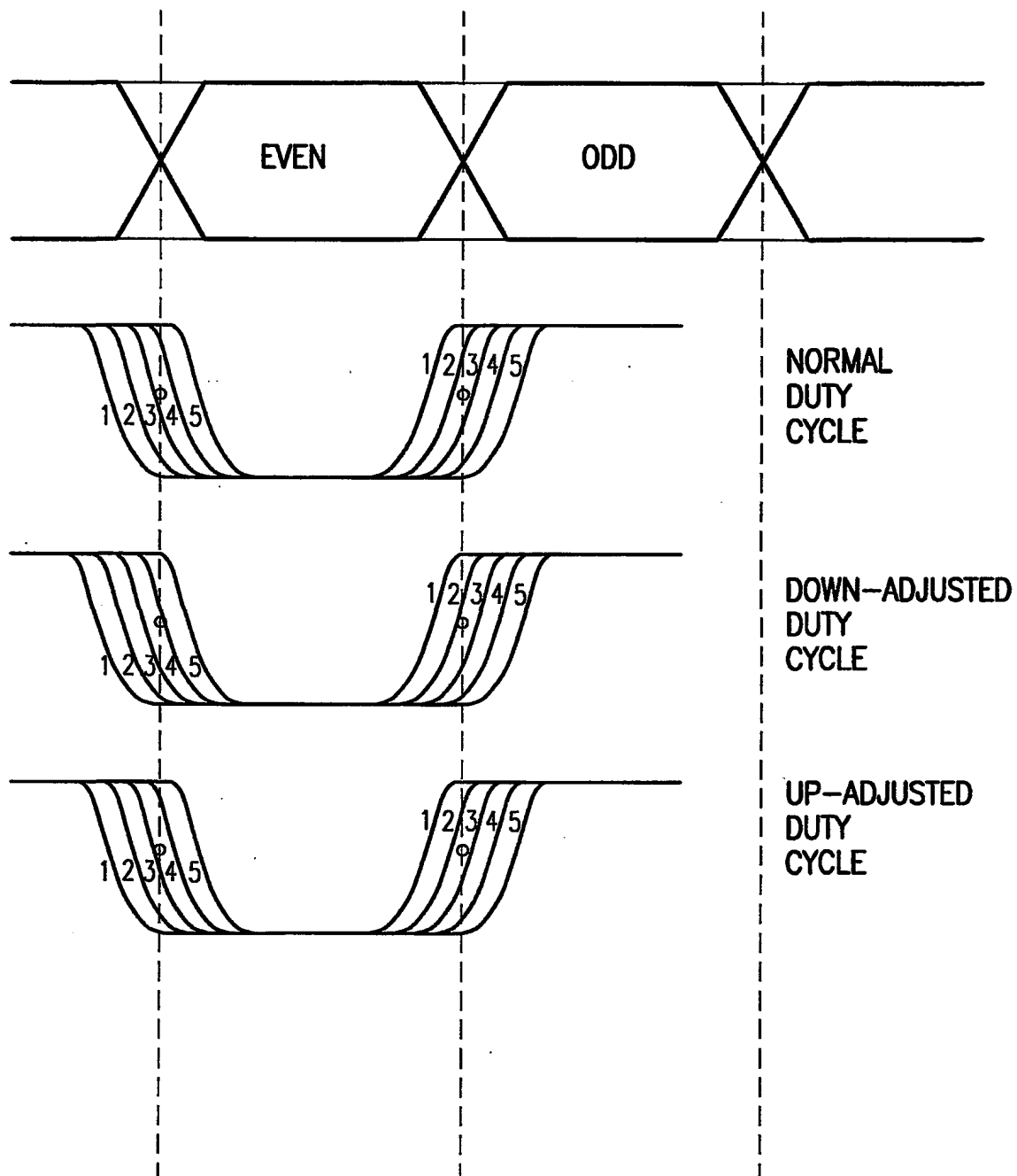


FIG.34

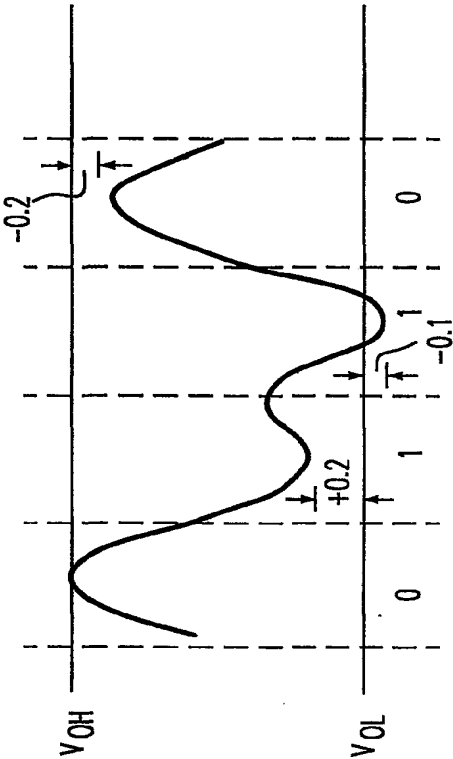


FIG. 35

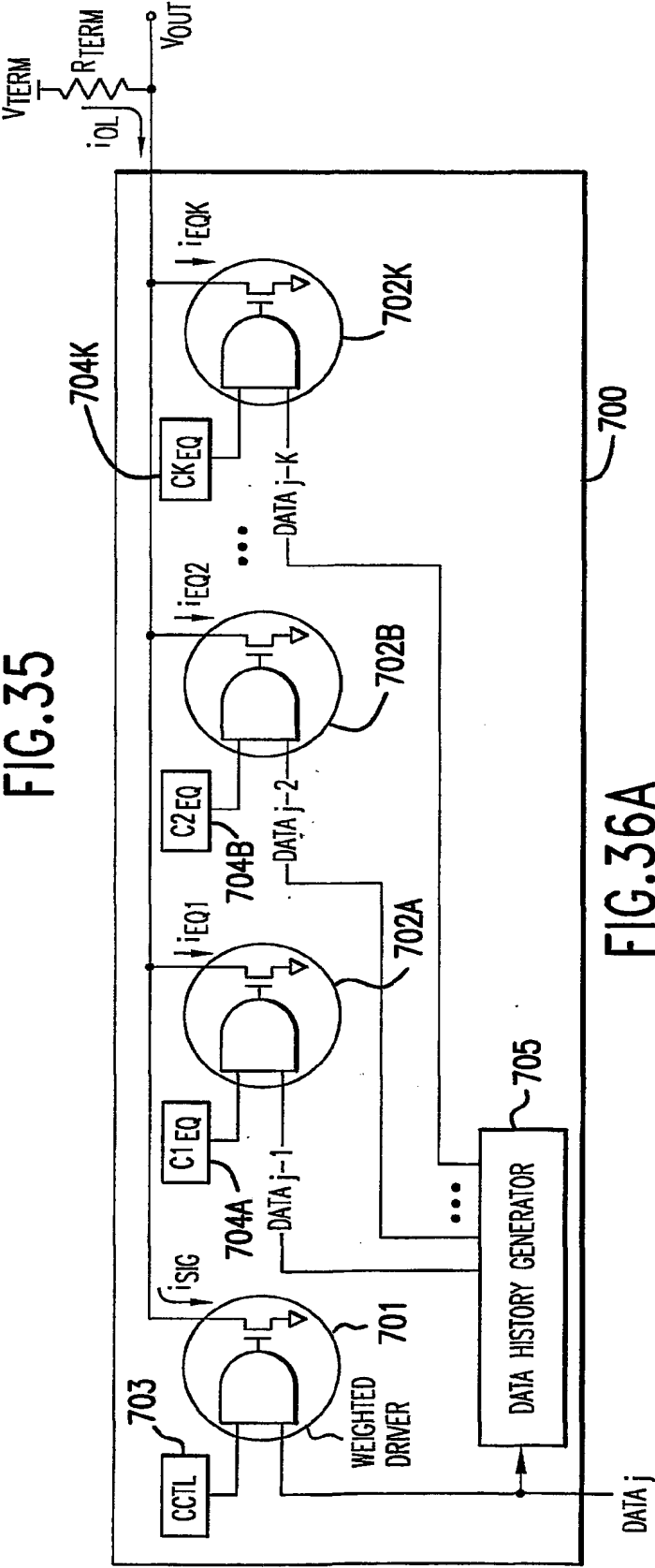


FIG. 36A

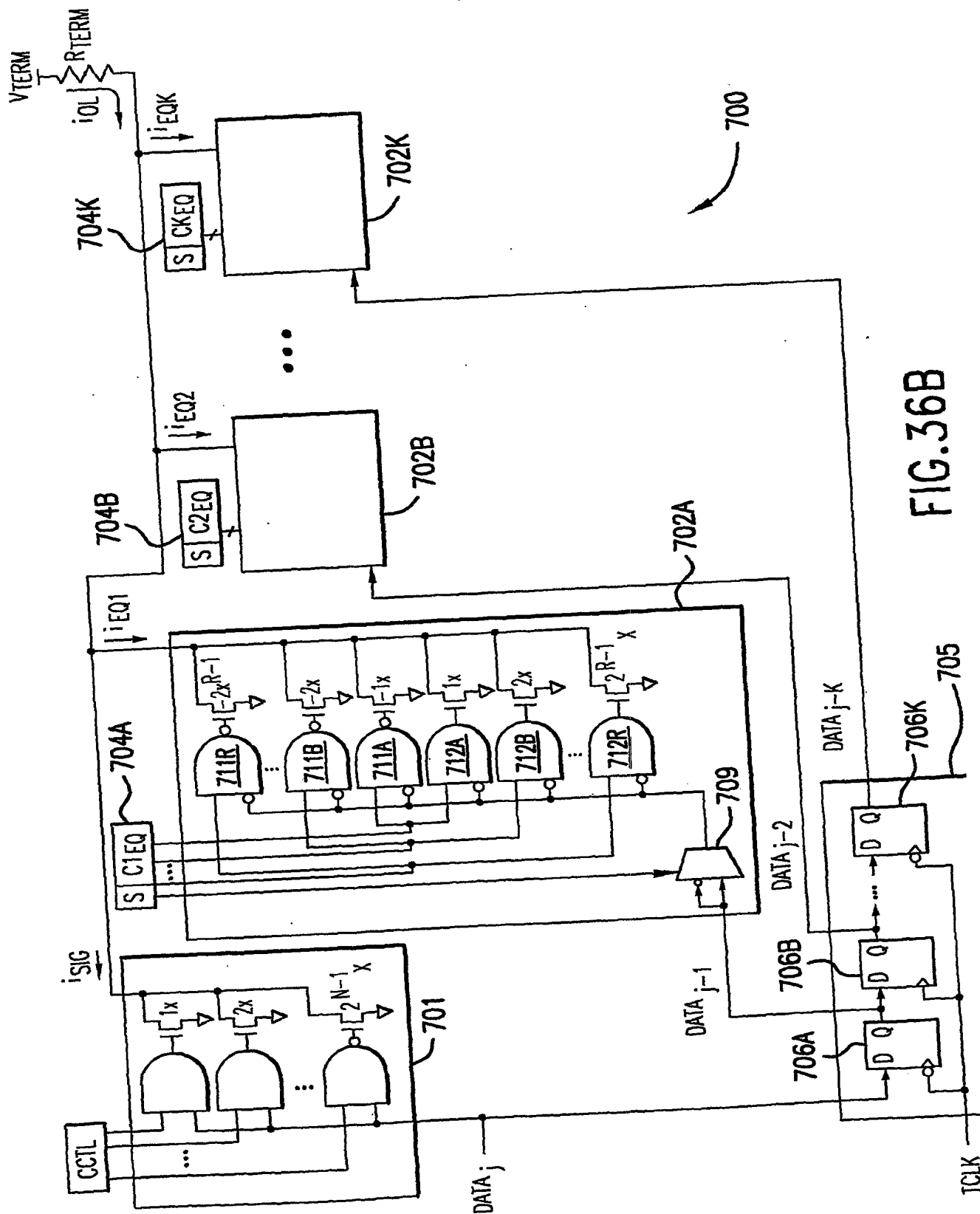


FIG. 36B

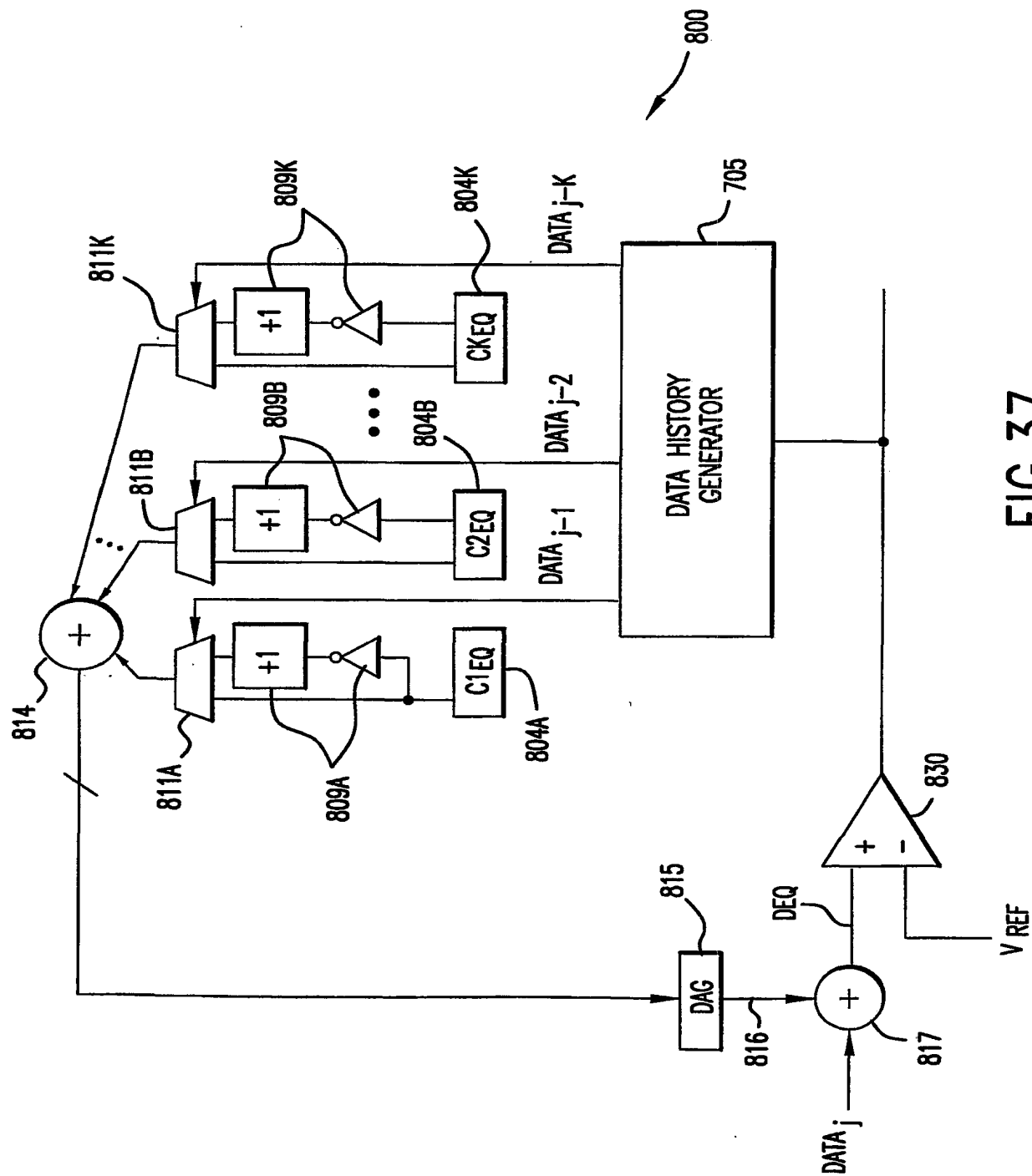


FIG.37

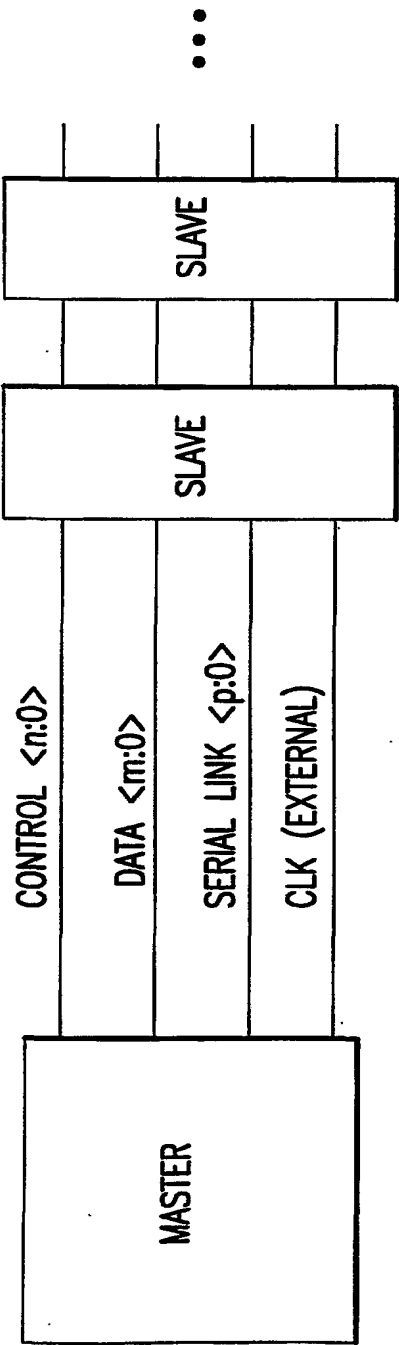


FIG.38

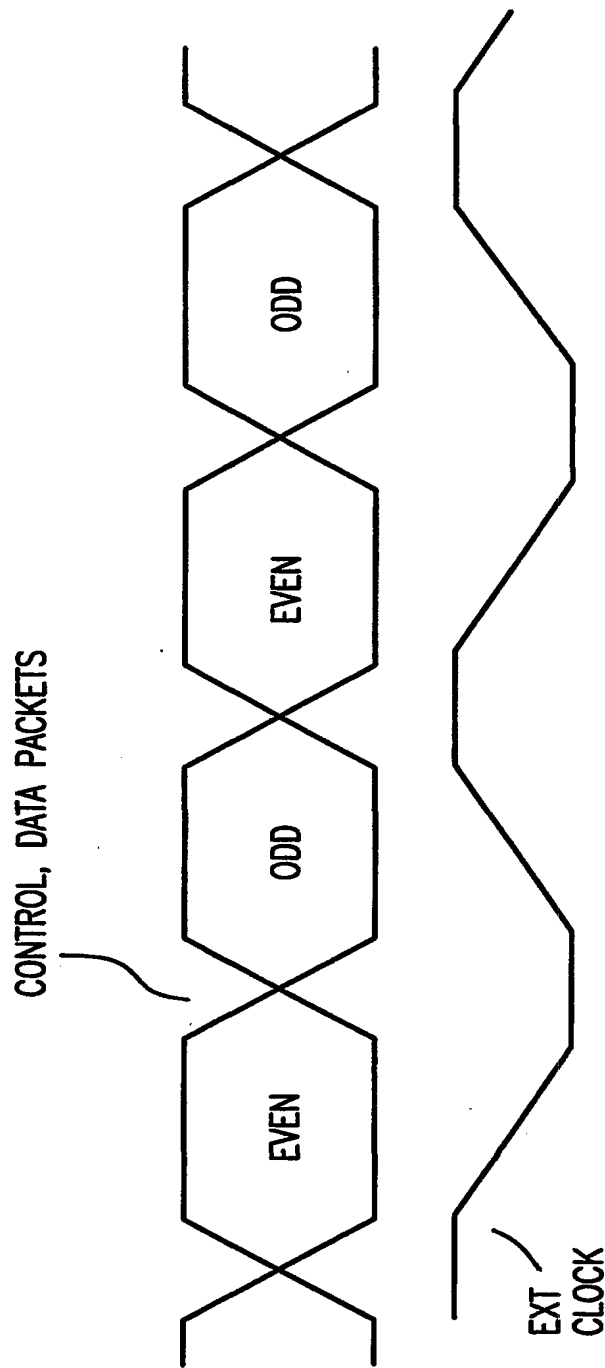


FIG.39

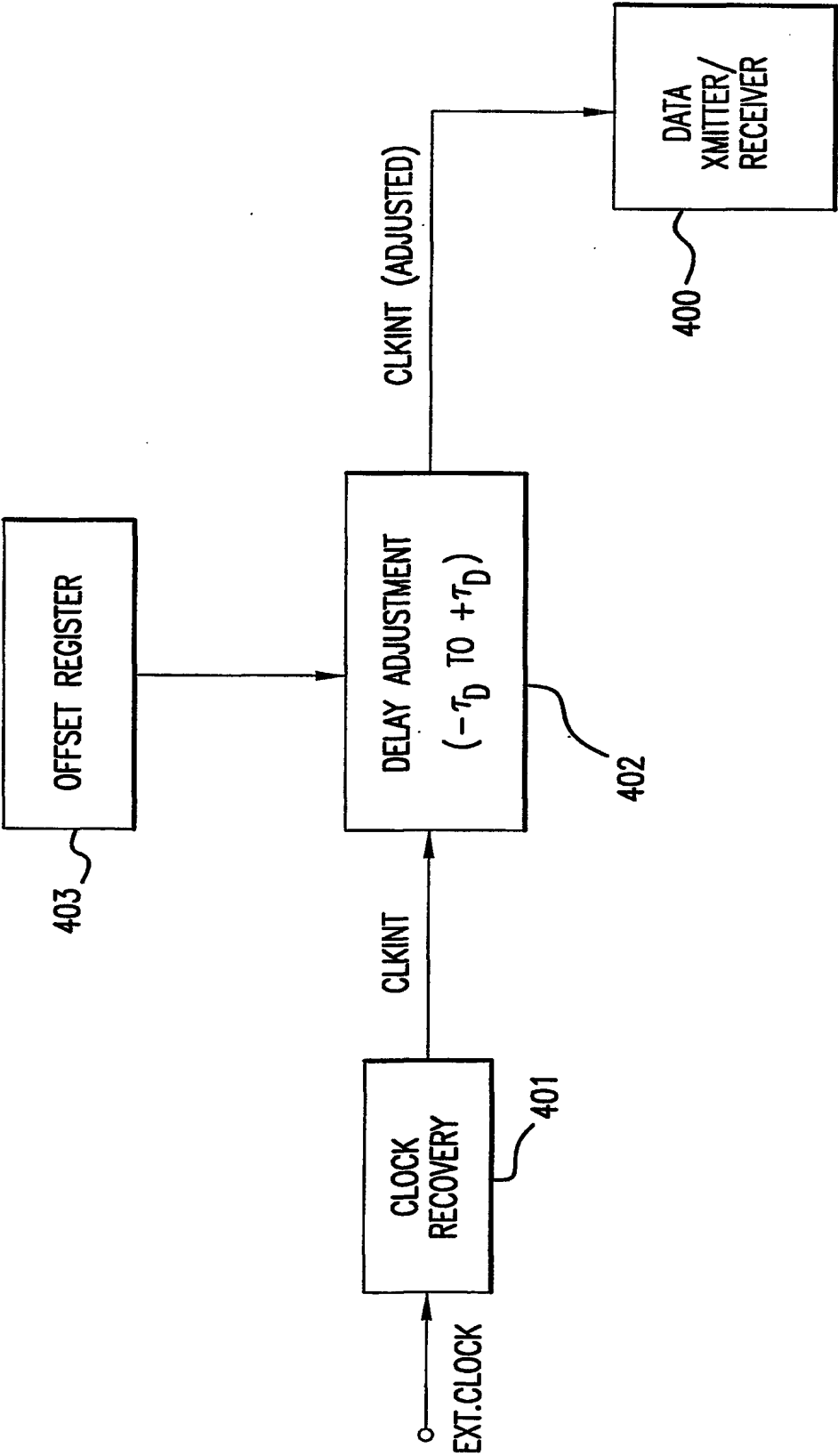


FIG. 40

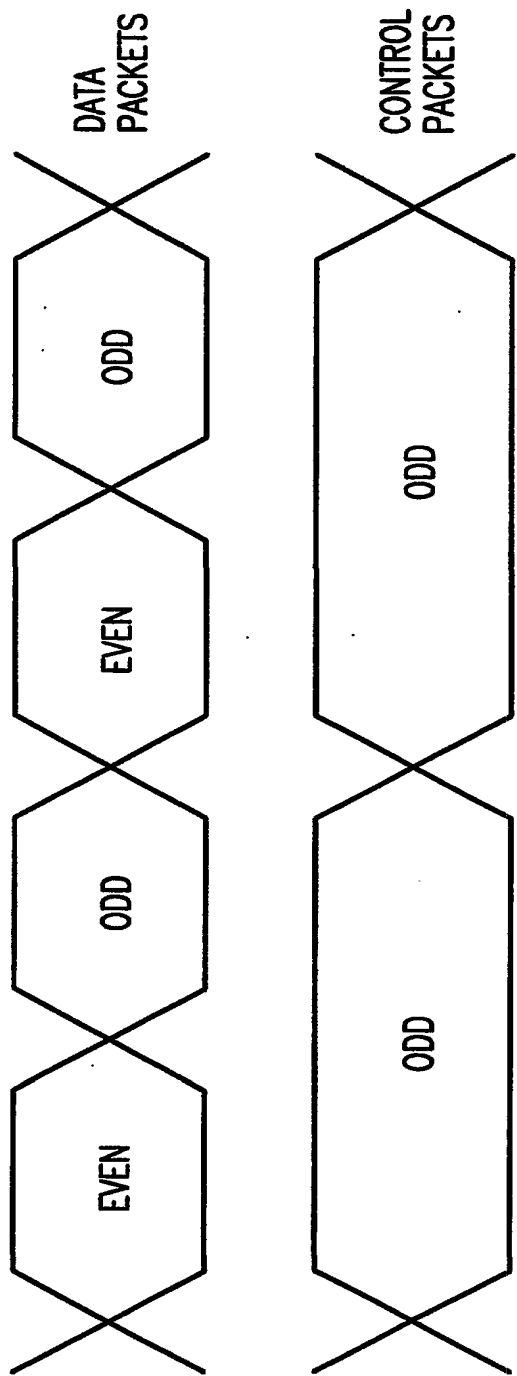


FIG.41

NORMAL OPERATION FORMAT						CALIBRATION MODE FORMAT					
	c[4]	c[3]	c[2]	c[1]	c[0]		c[4]	c[3]	c[2]	c[1]	c[0]
EVEN 0	D4	D3	D2	D1	D0		ST	03	02	01	00
ODD 0	ST	03	02	01	00		ST	03	02	01	00
EVEN 1	M15	M14	M13	M12	M11		A13	A12	A11	A10	A9
ODD 1	A13	A12	A11	A10	A9		A13	A12	A11	A10	A9
EVEN 2	M10	M9	M8	M7	M6		A8	A7	A6	A5	A4
ODD 2	A8	A7	A6	A5	A4		A8	A7	A6	A5	A4
EVEN 3	M5	M4	M3	M2	M1		X	A3	A2	A1	A0
ODD 3	M0	A3	A2	A1	A0		X	A3	A2	A1	A0

FIG.42

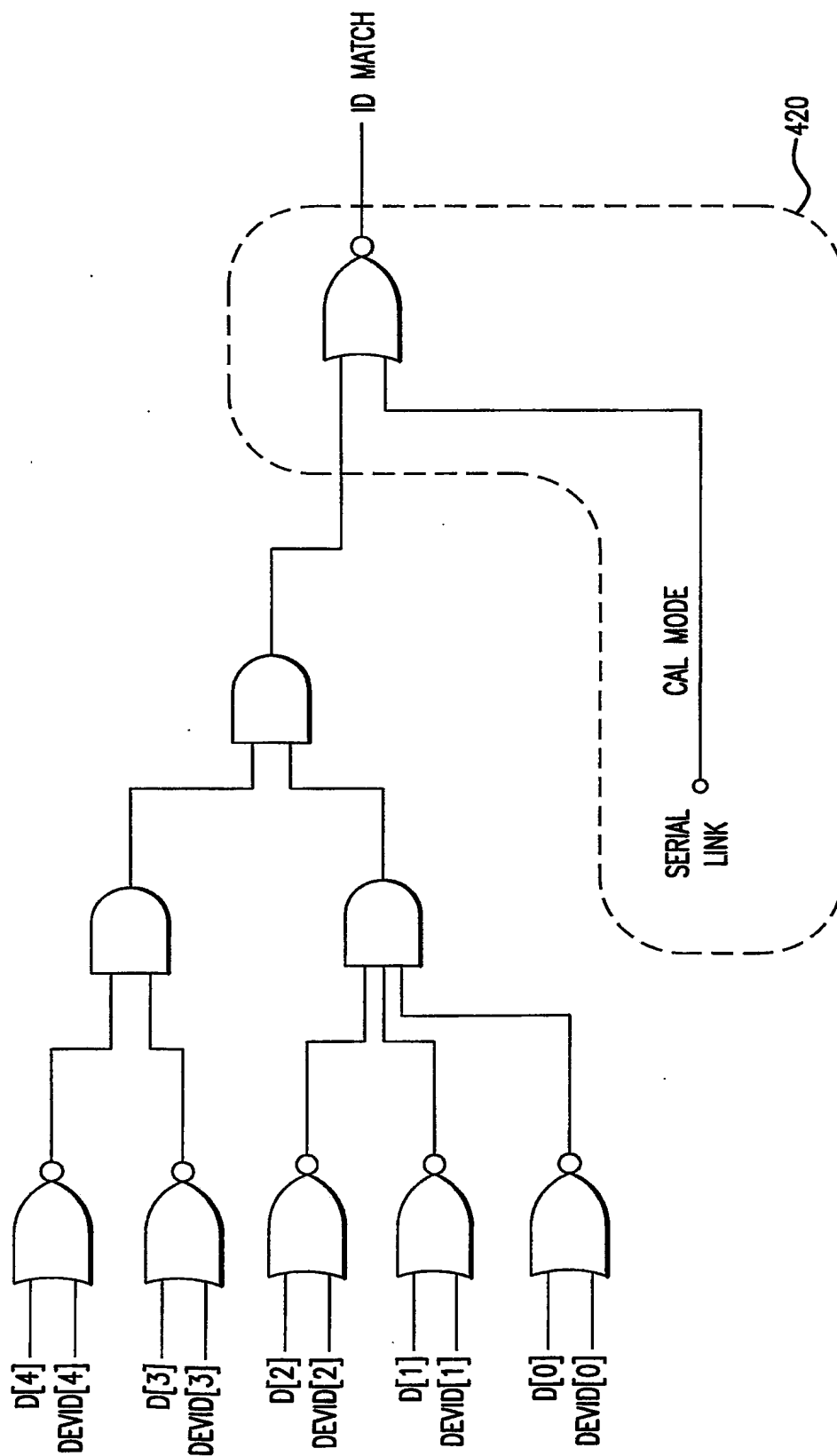


FIG. 43

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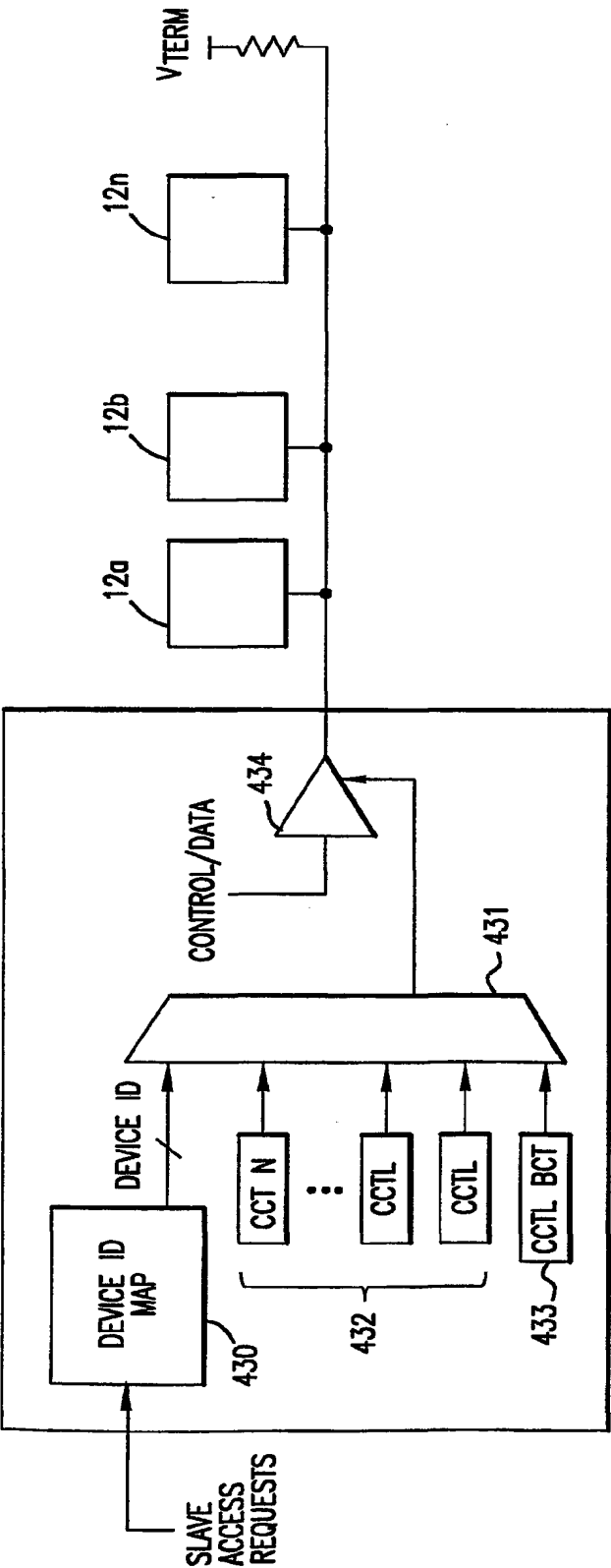


FIG.44

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/28134

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : G06F 13/42

US CL : 710/105

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 710/105, 107, 110, 106, 127, 25, 58-61

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
WEST, EAST

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X,P	US 6,085,284 A (FARMWALD et al) 04 July 2000, abstract, col. 4, lines 14-27, col. 18, lines 34-53, col. 19, lines 13-30, col.	1, 8, 17, 18, 22, 24, 34-38, 40, 41, 49, 52, 57, 62, 65-67, 69NO



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be of particular relevance	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E" earlier document published on or after the international filing date	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&" document member of the same patent family
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search

10 JANUARY 2001

Date of mailing of the international search report

16 MAR 2001

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